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PROJECT SUMMARY REPORT.

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PREFACE

This report was prepared within the Department of Civil Engineering, Dean of Faculty ([illegible]), United States Air Force Academy for the Air Force Engineering and Services Center (AFESC) under work unit [illegible] 3805. This work was accomplished during the period [illegible] to July 1980. Prior to 15 March 1979, this work was accomplished for the Civil and Environmental Engineering Development Office (CEEDO) which became the Engineering and Services Laboratory of the Air Force Engineering and Services Center.

This report has been reviewed by the Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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This report summarizes the solar energy research which was conducted by the U.S. Air Force Academy from April 1975 to January 1980. This research consisted of investigations on a retrofit space heating system which was installed on a typical Military Family Housing (MFH) unit. This summary uses a "lessons learned and designer tips" approach in its discussion of the solar system's operation. This discussion is organized around the many areas

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of solar technology which were investigated during the course of this project. Those major areas were energy conservation effects, solar collectors, thermal storage, control systems, thermography studies, performance comparison to a design model, and homeowner and maintenance manual development. A thermal performance summary of the solar system is also presented. The report concludes with numerous recommendations regarding policy initiatives which the Air Force should take to foster conversion to solar technology.

THE USAFA SOLAR ENERGY

RESEARCH PROJECT

SUMMARY REPORT

by

Captain Kenneth A. Cornelius, PE

ESL Technical Report 80-35

July 1980

Department of Civil Engineering
United States Air Force Academy
Colorado 80840

FOREWORD

This report summarizes work which was accomplished during the entire period of the solar research conducted at the U.S. Air Force Academy. The author therefore wishes to give primary credit for the results of this project to those who did it--the members of the research team, both past and present. They are too numerous to list, but particular thanks is due to one member of that team, Anthony Eden; his dedication and enthusiasm never faltered. The Project Director, Colonel Wallace E. Fluhr, also deserves special praise for his support and leadership throughout the project.

The author is also very grateful to Mrs. Carmen Villines and Mrs. Penny Grayson for their untiring efforts in finalizing the report. Mrs. Grayson's proofreading and editorial assistance were particularly valuable.

Last but not least, thanks should go to the personnel of the Air Force Engineering and Services Center for their patience and cooperation throughout this project's life. It is only hoped that the Air Force will benefit from this project as much as the investigators learned from it. It was a most challenging experience for all who were fortunate enough to be involved.

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The USAFA Solar Test House

CHAPTER 1

INTRODUCTION

1.1 Introduction

This executive summary is intended to be a concise history of the solar energy research that was conducted primarily by the U.S. Air Force Academy's Department of Civil Engineering. This project was the first experimental real property solar energy research that was conducted "in-house" by the Air Force and the Department of Defense. This report will describe the scope and nature of the research, summarize the performance of the Air Force Academy Solar Test House (AFA STH), itemize and discuss lessons learned in various areas of solar technology, and make recommendations regarding the future application of solar processes in the Air Force.

1.2 Project History

The origins of this project can be traced to the interruption of natural gas supplied to the AFA in early 1973. In September 1973 representatives of the Academy founded the Air Force Solar Energy Working Group and proposed various options for undertaking solar energy research to the commander of the Air Force Systems Command (AFSC). The AFSC initially, through the Alternative Fuels Development Office and later through the Frank J. Seiler Research Laboratory (located at the AFA), approved and funded by the project. Funding for continued research was provided by AFSC's Civil and Environmental Engineering Development Office and then

by the Air Force Engineering and Services Center located at Tyndall AFB, Florida. The actual project, to be subsequently described, began construction in July 1975. Active research continued on the project until January 1980 although funding ceased in October 1979. A short synopsis of project funding follows:

FY 75	-	\$44,500	(Acquisition)
FY 76	-	\$15,000	(Acquisition)
	-	\$10,000	(Test & Evaluation)
FY 7T/77	-	\$15,000	(Test & Evaluation)
FY 78	-	\$10,000	(Test & Evaluation)
FY 79	-	\$3,900	(Test & Evaluation)
		\$98,400	

This total does not include the nearly \$200,000 of unfunded labor and equipment which was contributed by the AFA throughout the life of the project.

1.3 Project Description

It was concluded in the early stages of planning that a retrofit space heating project would have the most benefit to potential future USAF applications of solar energy. Accordingly, a typical AFA, natural gas heated Military Family Housing (MFH) unit was selected to receive an active, liquid, flat plate collector system. The home had approximately 176 square meters (1900 square feet-SF) of heated floor space (includes 700 SF of unfinished basement) and was constructed in the late fifties using typical building techniques of that era. A total of 50.7 square meters (546 SF) of collectors (flat plate, liquid, nonselective surface copper absorbing plate, two layers of tempered glass covers) manufactured by the Revere Copper Corporation were initially installed; half of the

collectors were placed on a due-south facing roof array permanently fixed at 52^{o} inclination angle, while the remaining collectors were installed on a ground array in the back of the home. The ground array was also due-south facing but had the capability to orient the collectors at either 45^{o}, 52^{o}, or 60^{o} inclination angles.

The collector fluid (50% water and 50% ethylene glycol) releases its thermal energy via steel sheet and tube heat exchangers to an underground, 2500-gallon-capacity, reinforced concrete storage tank. The tank was purposely oversized to permit the investigation of various storage masses on the overall efficiency of the solar system.

The solar-heated hot water in the storage tank is pumped directly (no heat exchangers in the storage tank on the load side) to a water-to-air heat exchanger which was installed in the return air plenum of the existing forced-air heating system. The existing furnace fan was replaced with a larger unit (42.5 m^3/min -1500 cfm) which served both heating systems. A shell and tube heat exchanger was also installed in an effort to preheat city water before it entered the conventional water heater. This heat exchanger was plumbed into a separate loop which was connected to the solar storage tank. This loop possessed its own pump. The pump was activated (by a pressure sensing switch) only when hot water was being used. After some experience was gained with this system arrangement, it was felt that parasitic energy probably equaled the thermal energy gain. Accordingly, the system was disconnected and is no longer used.

The solar system and the home were completely instrumented to record all environmental and system parameters. All data was collected in fifteen-minute intervals and stored in a microprocessor-based system. The microprocessor, in addition to storing data, also controlled the home's solar

and auxiliary heating systems (i.e., turned pumps and fans on and off, etc.). It is felt that the extent and accuracy of the data which was collected during the course of this project has been seldom equaled in other solar research installations.

An attempt was made early in the project to correlate the solar home's conventional energy savings to a control house. This home was located nearby and was identical in construction and orientation. It was instrumental thoroughly and data was obtained, but correlation of the two homes' energy consumption proved almost impossible. Differences in family size, lifestyle, etc. were considered to be the primary reasons for this difficulty.

A schematic of the solar system is shown on Figure 1-1.

Changes were made to the various system components during the course of the project and are discussed in Chapter 2. The final configuration of the system is essentially as given above with the exception that 47.1 square meters (507 SF) of collector area (vice 546 SF) is installed (4).

1.4 Published Research Reports

There were four annual technical reports published during this project.

- Solar Heating Retrofit of Military Family Housing, Frank J. Seiler Research Lab Technical Report 76-0008, September 1976, Air Force Systems Command.

- Second Interim Technical Report on USAFA Solar Test House, FJSRL Technical Report 77-0016, Civil and Environmental Engineering Development Office (CEEDO) Technical Report 77-34, September 1977, Air Force Systems Command.

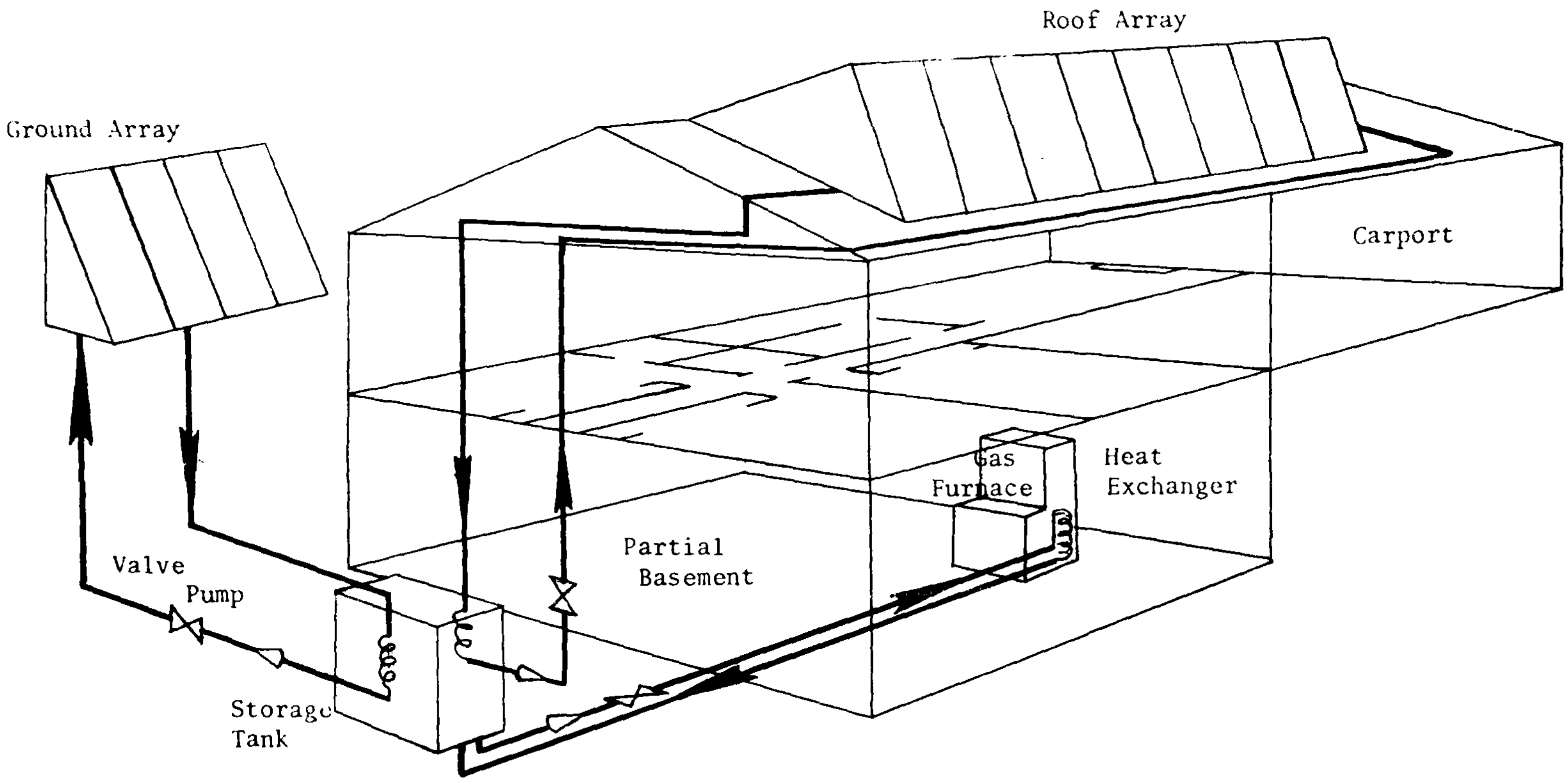

Figure 1-1. USAFA Solar Home System Schematic

- Third Interim Technical Report on USAFA Solar Test House - Design Parameters, CEEDO Technical Report 78-32, September 1978, Air Force Systems Command.

- Final Interim Technical Report on USAFA Solar Test House, Engineering and Services Lab (ESL) Technical Report 80-34, Air Force Engineering and Services Center.

Although these reports are listed as references 1-4, they were used so extensively in the preparation of this summary that they are not specifically cited. The reader is urged to review these annual reports for more detailed information regarding the topics discussed in this summary.

CHAPTER 2

PROJECT SUMMARY

2.1 Initial Project Objectives

The initial project objectives were:

- Develop and/or substantiate design criteria for solar thermal heating systems.

- Obtain design, construction and operation, and maintenance criteria.

- Obtain sound cost data upon which to model future economic decisions.

It is felt that much valuable information regarding the first two objectives has been obtained and reported. Due to the extremely high costs involved in the acquisition and modification phase of the project, however, it is not believed that sound economic information can be formulated. The high costs experienced in constructing this project reflect its research character and cannot be related to costs that would be encountered in a nonresearch application.

2.2 Research Areas Investigated

The different areas of solar technology which were investigated during the course of this project are listed below for easy reference. Condensed comments reflecting lessons learned and design tips regarding each topic area are given in succeeding sections of this chapter.

- Energy Conservation Effects
- Solar Collector Systems
    - Collector Placement (Ground vs Roof Arrays)

- Collector Orientation/Inclination Angles
- Fluid Flow Rate Variations
- Flow Rate Control Theory (Bang-Bang vs Optimization)
- Air Blockage Effects and Control
- Piping, Pump, and Valve Configurations
- Evacuated Tube and Flat Plate Collector Comparison
- Collector Cover Removal Effects

- Thermal Storage System
  - Tank Type and Placement
  - Storage Mass Variation Effects
  - Usable Storage Temperature Levels
  - Heat Exchanger Interface
- Microprocessor Control Systems and Sensors
- Thermography Studies
- Design Model Comparison to Actual Performance
- "Homeowner" Manual Development
- Maintenance Manual Development

2.2.1 Energy Conservation Effects

Using design criteria in effect at the time of construction the original design heating load for the home was 74.4 MJ/hr (70,430 Btu/hr). Consequently, the original gas furnace which is still used as the auxiliary heating system, has a maximum rated capacity of 87.7 MJ/hr (83,000 Btu/hr) at an air flow rate of 37.8 m^3/min (1333 CFM). With more stringent criteria in use in 1976 the design heat load had reduced to approximately 53.9 MJ/hr (51,000 Btu/hr). In February of 1977 the level of insulation in the home was significantly increased. Urea formaldehyde foam was injected in all the walls and six inches of loose fill was blown into the roof

joists. This increased the calculated wall and ceiling R values from 8.2 to 15.8 and from 14.5 to 34.5, respectively. Three-inch fiberglass batts were also added between floor joists over the crawl space.

Vestibules for the two entrances were also constructed during this time period. A triple glazing consisting of an interior-mounted storm window was also added to all windows in the summer of 1977. Other conservation measures have also been undertaken on the home (e.g., electronic furnace ignition, furnace flue damper, etc.). The calculated heat demand of the structure decreased to approximately 38.4 MJ/hr (36,400 Btu/hr), primarily as a result of the wall and ceiling insulation improvements. This represents a 28 percent reduction in calculated heat demand for a $1,125 investment for these two measures. Actual data regarding the seasonal heating demand correlated with the predicted reduction in energy consumption very well.

One consequence of "tightening" a solar augmented structure, which is still too often overlooked, is its impact on the apparent efficiency of the installed solar system. If the total energy demand of the facility is reduced, as it was in this project (by approximately 30 percent), then the load fraction contributed by the solar system will increase for a given environmental condition. In actuality, of course, this result does not necessarily represent an increase in the solar system's "efficiency". One must be cautioned not to confuse a solar system's efficiency with the fraction of the total load which it contributes.

The following data clearly demonstrated this result for this project.

TIME PERIOD	SOLAR FRACTION OF TOTAL ENERGY PROVIDED
76-77 Heating Season: Oct 76- Jan 77	38%
(pre-conservation measures)	
Feb 77 - Apr 77	58%
(post-conservation measures)	
77-78 Heating Season:	
(post-conservation measures)	
Oct 77 - Jan 78	57%
Feb 78 - Apr 78	66%

Notice that the fraction of the total energy supplied by the solar system increased by almost 20 percent for the comparable time periods which contrast the structure before and after the additional insulation was installed. This fraction increased only 8 percent for the other time period (Feb-Apr) which reflects the additional insulation having been installed in both seasons. Environmental conditions, as measured by the number of heating degree days, for all comparable time periods were very similar. It must be pointed out that improvements in solar system operation and efficiency were made in the second winter, however, these data nevertheless prove dramatically the sensitivity of the solar load fraction to the degree of conservation measures implemented in the structure. In short, this project conclusively showed that reasonable investments in conservation improvements should be made prior to, or concurrently with, any proposed solar modifications.

As stated previously, the increased wall insulation installed in this project was urea formaldehyde (UF) foam. USAF directives prohibited the use of this material, but special approval for its installation was granted for this project. (The prohibition was based on concerns regarding the effect of the water used to inject the foam.) The foam was installed into

existing wall cavities by drilling holes and pumping it through pressurized hoses using specialized nozzles and pumping equipment. Original fears regarding the effect of the high volumes of water used to inject the foam in the wall structure were unfounded. No deterioration of the gypsum wall-board or paint occurred. One section of a wall interior was inspected eight months after injection and no shrinkage or cracking of the foam was observed. In addition, the original rock wool insulation had not been affected.

The U.S. Consumer Product Safety Commission and others have reported that UF foam may release formaldehyde gas into living areas. This gas can cause upper and lower respiratory problems, headaches, and other poorly understood health problems in humans. To investigate this potential problem the Frank J. Seiler Research Lab was requested to determine if any formaldehyde vapors could be detected in the home. On 18 January 1980 an approved air sampling device, developed by OSHA, was placed in the home. At least 336 liters of air were drawn through the sampler and the adsorbent material was subsequently checked for the presence of formaldehyde gas. The equipment used was capable of detecting components in the parts per million (ppm) range; no substances were detected. The UF foam is believed to have been safe, to date, in this project. It is an effective insulating material but extreme caution must be exercised in any future installations due to the potential health problems.

2.2.2 Solar Collector Systems

Numerous areas of collector technology were investigated during the course of this project. The following areas are deemed of sufficient significance to be included in this summary.

2.2.2.1 Collector Placement

A unique aspect of this project was the decision to place the collectors on a roof array and a ground array installation.

This allowed comparison of these two basic alternative locations with regard to installation, performance and maintenance considerations.

The designer should consider current and future shading, structural loading, snow accumulation potential, aesthetics and cost (both installation and maintenance) when deciding on roof versus ground-mounted collectors. The comments which follow regarding these factors are intended to aid a designer in making this basic decision.

The problem of shading must not only be considered for current conditions; the effect of future facility construction and growth of trees in the area should also be evaluated. There are numerous methods available in the literature to calculate shading distances and thereby determine collector location and spacing requirements. The simplified procedure given in the Installation Guidelines for Solar DHW Systems published by the U.S. Department of Housing and Urban Development is probably as good as any. Collectors should obviously be placed where the maximum amount of sunshine will be available during the maximum energy demand period. This statement ought to be tempered with the realization that a 100 percent shade free location may not be justified in all applications. Shading concerns will generally argue for a roof placement for collectors but other considerations, discussed subsequently, may override them.

Structural loading considerations may rule out a roof installation. An analysis of the roof truss for this project dictated the requirement of adding a web to support the additional weight of the collectors which was close to 13 pounds per square foot. In order to achieve the desired collector inclination angle this project utilized a "parasite truss" on the existing structural members of the roof. This

necessitated removal of the roofing material and placement of new support sheathing and waterproofing measures (plastic sheeting, flashing, etc.). It was discovered that both neoprene and hypolon type of plastic and a conventional 10 mil thickness plastic sheeting would be melted by stagnant collectors. No roof leaks have developed, but waterproofing problems must be carefully considered on any roof placement scheme. If structural and aesthetic concerns permit their use, a retrofit project should probably use a mounted framework to support the collectors. This technique should be more economical and will minimize roof penetrations and leakage fears.

If a framework is used, the structural implications of wind loading must be thoroughly investigated. These loadings will no doubt exceed the dead weight of the collectors themselves. Particular attention should be given to connections both from a structural and waterproofing/drainage standpoint (e.g., install sleepers in such a manner to prevent ponding or damming of water, etc.). It should be mentioned that the back and edges of frame-mounted collectors will be exposed, thereby potentially resulting in greater thermal losses and decreased efficiency. If good quality collectors are used, however, this factor should not be significant. The raised collector support design used in this project's ground array has proven satisfactory from all structural considerations. It has been exposed to extremely high winds, and no problems have been encountered. Details of this design are available in this project's first interim technical report.

If a ground array installation is used, the designer must choose between above- or below-ground piping connections. This project used subsurface piping primarily for aesthetic reasons. Care should be given to frost line penetration depth and soil moisture conditions; these will determine the amount and type of piping insulation

required. Most authorities call for at least R-4 insulation, wrapped in roofing paper sealed by hot pitch. The number of joints in buried pipe runs should be minimized as well as runs under paved areas. Standards regarding pipe placement in trenches and backfill practices should be strictly enforced for solar collector applications. A significantly higher investment is at stake in solar projects than would normally be encountered in a typical underground pipe leak. Pipe runs through or under foundations should be encased in a sleeve larger than the insulated pipe with the ends sealed by moisture-resistant material.

No significant difference in performance of a roof versus ground array was noted during the course of this project. (Differences were noted but it is believed they were attributable to other differences between the two arrays, e.g., inclination angles, number of heat exchangers on each array in the storage tank, the length of pipe runs between the collectors and storage, etc.)

One area of difference which does deserve comment, however, is with regard to snow accumulation on the collectors. Since the roof array collectors in this report were installed as an integral part of the roof (i.e., not raised above the roof by frame mounting), snow would not dissipate as quickly from it as for the raised ground array. The contiguous roof to the collectors was at a less steep slope, and melting snow from the collectors would therefore tend to accumulate at the bottom of the collector panels. After a severe storm the roof collectors would not be completely cleared for perhaps three to four days, whereas the raised collectors on the ground would clear in two to three hours.

This problem can be solved by either raising the collectors above the roof with frame mounts or placing them on the edge of a roof

where the snow may slide off directly to the ground. If this latter option is used, avalanche protection for pedestrians or changed sidewalk locations should be considered.

Maintenance and cost considerations generally favor a ground array installation. There is no question that access to collector panels for whatever reason (sensor replacement, fluid draining or recharging, etc.) is much easier and cheaper for ground installations. The ground array for this installation was fenced and underlaid with plastic and gravel to retard vegetation. It is recommended that this procedure be followed to preclude the cost and inconvenience of mowing the "collector field".

If an ethylene glycol based, liquid collector system is used on a roof array, consideration should be given to guttering the collector panels. Ethylene glycol, if allowed to contact asphalt material, either shingles or built-up roofing, will result in significant deterioration. The asphalt shingles "down slope" from the roof collector on this project have become brittle and will unquestionably require replacing earlier than they otherwise would. An installation on a flat, built-up roof where ponding might occur could have even more rapid and serious consequences.

If collectors are mounted as an integral part of the roof, provision for relatively easy access to this space must be made. Adequate room for workmen behind the collectors should also be provided if at all possible. Consideration might also be given to provision of protective walkways to prevent damage to roof material from maintenance equipment (ladders, etc.) and foot traffic.

Provision of a simple and cheap "catwalk" near the top of a frame-mounted collector array (either ground or roof) is also recommended. If connecting plumbing is covered by sheet metal, provision of access ports over key valves and drain locations should be used. The sheet metal covering between collectors on this project represents an example of how not to do it; often it was necessary to remove practically all of it to just gain access to one particular location. The designer should be cautioned not to overdesign these maintenance aids because a reasonably well operating system should not require frequent or prolonged access.

Other miscellaneous considerations which could impact the selection of a collector location are vandalism potential, reflected glare from the glass covers, pipe run lengths and parasitic power required to pump collector fluid. Pipe run lengths should be minimized to prevent excessive heat and head losses and to lower installation costs. Since ground-mounted collectors will probably have less static head they will require smaller pumps and thereby reduce parasitic power consumption. (Data available for this project indicated that the roof array collector pump consumed approximately 6 percent more power and delivered less thermal energy than the identical ground array pump even though the pipe run distance for the ground array was twice as far.)

To summarize, the decision on placement of collector arrays requires the investigation of many variables. Each installation will present different circumstances and may, therefore, call for different answers.

2.2.2.2 Collector Orientation/Inclination Angles

Another unique aspect of the collector installation for this project was the capability of the ground array to be placed at

different inclination angles. The roof array was fixed at a 52^{o} angle (with respect to horizontal) whereas the ground array could be oriented at 45^{o}, 52^{o}, or 60^{o}.

The ground array was operated at 45^{o} during the first winter of operation (75-76). On 1 October 1976 the angle was changed to 60^{o}. On 24 May 1977 the array was again placed at 45^{o}, and on 1 October 1977 it was moved to the 52^{o} inclination. Both arrays operated at this inclination for the remainder of the project.

Based on the data obtained during this project, it was concluded that collector efficiency (i.e., energy collected ÷ energy available) did not improve as a result of more favorable inclination angles during the year. Total amounts of energy collected did, of course, increase when the ground array was placed at angles more near optimum for a particular time of year.

For the inclination angle settings available for this project and latitude (38.8^{o}N) the following changes were determined to maximize collected energy:

TIME PERIOD	PREFERRED ANGLE
3 Oct - 3 Nov	52^{o}
3 Nov - 20 Feb	60^{o}
20 Feb - 3 Mar	52^{o}
3 Mar - 3 Oct	45^{o}

It must be pointed out that it may not be desirable to maximize energy available during all times of the year. For instance, if space heating is the primary objective of a particular installation and the storage tank is located inside the structure, maximizing energy gain to

storage in the summer months would place a greater heat load on air conditioning systems.

It should also be noted that during high heating load periods (3 Nov - 3 Mar) that the 60^{o} tilt maximized collected energy 90 percent of the time (approximately 110 days out of the 120 day period). This inclination angle corresponds to latitude plus 21^{o}, not the often-recommended rule of thumb of latitude plus 10^{o}-15^{o}. It is nevertheless felt that use of these recommended compromise tilts will not greatly affect system performance. Another consideration which must not be forgotten is the greater cost involved in constructing and operating a movable array. Changing the angle required a 3-4 man crew for approximately one hour.

The compromise angle generally recommended for heating applications is latitude plus 10^{o}-15^{o}, and for cooling applications is latitude minus 10^{o}-15^{o}. An inclination angle equal to the latitude would maximize total annual solar availability. This would probably be desirable for a "pure" domestic hot water (DHW) project.

Applying these rules to this project would call for an angle from 49^{o}-54^{o}. Since the final setting in use for both arrays is 52^{o}, this represents a reasonable compromise.

Since both collector arrays are oriented due south, no information regarding the effect of azimuth angle can be reported. True south (not magnetic) orientations are, of course, recommended but most authorities feel that a 15^{o} variation (east or west of south) would have little effect on system performance.

2.2.2.3 <u>Fluid Flow Rate Variations</u>

Average flow rate of collector fluid is probably the operational parameter which has the greatest effect on collector efficiency.

Both collector arrays had identical pump and valve arrangements. The flow rate through each array was controlled by a microprocessor-activated and motor-driven variable valve. The pumps were purposely oversized to permit a wide range of available flow rates to both arrays. They provided a capability of from .126 to 1 liter/sec (2 to 16 gallons per minute-gpm).

During the first winter of operation (75-76) the flow rate to each array was permitted to reach 1 liter/sec (16 gpm) at full open position. This equated to an average rate of approximately .04 liter/sec per square meter of collector area (.059 gpm per square foot). This flow rate resulted in extremely high collector efficiencies, sometimes reaching 70 percent.

Prior to the second winter the maximum flow rate permitted was cut in half. This reduction resulted in more uniform flow patterns in the collector arrays as determined by thermography analysis (to be discussed later in this report). The most dramatic effect of the reduction, however, was the effect on the temperature differential imparted to the collector fluid. Prior to the change a good collection day would result in a $6^{o}C$ ($10^{o}F$) fluid temperature rise, whereas, afterwards it would sometimes reach $12^{o}C$ ($20^{o}F$). This higher temperature differential was obtained at the expense of reduced collector efficiency. This sacrifice proved to be worthwhile since the higher temperature collector fluid would raise the storage tank temperature to higher levels. Consequently, longer utilization of the solar heated storage water for home heating was made possible. In essence, solar <u>collector</u> efficiency was sacrificed to improve solar <u>system</u> efficiency, and a higher solar fraction of the total energy provided to the home was attained.

A brief explanation of the reduction in collector efficiency is as follows: If fluid flow rate is high, most of the energy absorbed by the collector is rapidly removed; this results in a relatively "cool running" collector. Conversely, with lower flow rates the collector fluid temperatures and the collector itself will be hotter. A "hot running" collector will, of course, experience greater thermal losses to the environment thereby resulting in decreased collector efficiencies.

The collector flow rate which optimized system performance for this project was determined to be .25 liter/sec or .01 liter/sec per square meter (4 gpm-.015 gpm/sf). This flow rate resulted in average collector efficiencies of 20-40 percent during the heating season. Even with these much lower collector efficiencies the maximum amount of solar energy was delivered to the facility for the reasons discussed above. (This flow rate is very close to the often recommended limits of .02-.04 gpm/sf for liquid flat plate collectors.)

In summary, the designer must size collector pumps, piping and valving carefully in an attempt to achieve optimum collector flow rates. Careful design and proper operation can achieve the same solar energy contribution as an improperly designed but much larger area collector system.

2.2.2.4 Flow Rate Control Theory (Bang-Bang vs Optimization)

The high dependence of collector efficiency on collector working fluid flow rates has been previously discussed. Original project planning attempted to take advantage of this fact by installing a microprocessor controlled variable valve on both collector arrays. The variable valve system tried to optimize collection efficiency for various environmental and system conditions. This optimization control scheme is opposed to the more conventional bang-bang controller which provides

for only two operational settings--either complete shutdown or full open to the desired maximum flow rate.

The optimization scheme's description is as follows. When the collector plate temperature was 12°C (20°F) higher than the storage tank water, the variable valve opened to its midsetting (i.e., one-half of the desired full open flow rate) and the pump would come on. Control then switched to a comparison of the collector fluid exit temperature to the storage tank water temperature. If the temperature difference between these parameters reached 1.7°C (3°F) or less, the variable valve would close incrementally every eight seconds. If the 1.7°C (3°F) ΔT would not improve as a result of the lowered flow rate the valve would continue to close until it reached one-fourth of the full open position at which time collector system shutdown would occur. Higher incremental valve settings would occur every eight seconds if the ΔT between the collector fluid exit and entry temperatures were 6°C (10°F) or greater.

This control strategy essentially provided two benefits. First, the reduced flow rates imposed during shutdown extended the time periods for collection of energy, i.e., it delayed complete system shutdown. It must be remembered that during these periods conditions were marginal and not much total energy was being collected. Storage tank temperature increases were rarely noted during periods of collector shutdown.

Secondly, collector efficiency was improved by forcing a higher flow rate through them if the working fluid temperature rise through the collectors (entry vs exit) exceeded 6°C (10°F). It should be noted that this type of strategy is not necessarily optimal, it may provide more energy under some conditions but not under others. At no time, for example, was an effort to include the costs of parasitic pump

power in the control scheme. There is little question, however, that it probably represented some improvement over a bang-bang strategy.

As a result of experience gained with this system, it is felt that a bang-bang controller would have proven acceptable in all but very marginal conditions. To implement a variable control strategy probably requires a microprocessor-based control system and a motor-driven variable valve. Simplicity is improved and extra expense avoided if a bang-bang control strategy is employed. Accordingly, when the research instrumentation was removed and the home was prepared for turnover to the Base Civil Engineer, a simple on-off system was used. The system continues to function well with this strategy.

2.2.2.5 Air Blockage Effects and Control

One of the most perplexing problems, and one which was encountered throughout the project, was air entrapment in the collectors. When air (or collector fluid vapor) collects in a portion of a solar collector, the flow of working fluid through that area is decreased or, under severe conditions, completely blocked. The temperature in this area will rise and may eventually vaporize additional nearby working fluid. If not allowed to escape, this air/vapor mixture can spread and could eventually render a complete collector array inoperable. The pressures attained in a "vapor locked" collector can also become very high and cause activation of pressure relief valves with subsequent loss of working fluid or even damage the plumbing system itself. Air blockage will more normally result in persistent decreased efficiency of the collectors.

The vents originally installed were 1 inch by 1/2 inch fiber pad valves commonly used on steam systems. They were replaced by

a low quality, float type, automatic air vent, rated at 30 psi (gauge), at the high point of <u>each</u> collector. It was later theorized that the installation of such a high number of low quality vent valves actually allowed air to enter the system at night as the collector fluid cooled and contracted. It is possible that the expansion tank used in this project should have had a higher pressure air charge than the standard 12 psi which was used. A higher pressure air charge could have helped prevent the theorized suction condition in the collector high points from developing. During the daytime, if some air <u>was</u> present, the vapor lock situation, outlined previously, began to develop with resultant localized high pressure conditions. Consequently, some of the vent valves failed completely with subsequent loss of working fluid.

Detection of the air blockage problem was based primarily on the presence of elevated temperatures in some collectors or of higher loop pressures than considered normal. The temperature detection method was made possible by the high number of installed sensors, particularly on the ground array. (Detection by thermographic techniques will be discussed in a subsequent section of this report.) It is unlikely that a nonresearch project would be aware of this problem unless it resulted in near shutdown of a collector array. It behooves the designer, therefore, to take every reasonable precaution in an effort to preclude this problem.

The ground array, due to its accessibility, was chosen as the primary test bed for modifications to solve this problem. The system which performed best was installation of 75 psi (gauge) high quality, automatic vent valves; one valve per four collectors was used. (The four collectors are interconnected at their high points by 1/4 inch

copper tubing.) It is critically important that air vent valves be placed at the high point of all collector loops. Provision of air eliminators (i.e., separators) in conjunction with the vent valves may also be warranted. A petcock to isolate the air vent valves is recommended to aid in their replacement. It should also be mentioned that the vent caps must not be tightened. A complete cluster of four collectors was found almost completely blocked due to air entrapment in the latter stages of the project; subsequent investigation showed that a workman had inadvertently tightened the vent valve cap. This simple oversight prevented any useful return from a nearly $1000 investment in the affected collectors.

2.2.2.6 Piping, Pump, and Valve Configurations

In any collector installation the designer is faced with the decision of choosing between a parallel, series, or combination plumbing arrangement. For an installation of any size a parallel/series combination is usually required in order to obtain maximum thermal gain for minimum pumping energy. Collector manufacturers' specifications generally provide guidance on this issue. This project used a series connection between four collectors and these series "clusters" were connected in parallel (some clusters consisted of only three collectors).

Original plans called for equalizing flow, and therefore performance, through all collectors by use of balancing valves. Pressure gauges were installed later in an attempt to determine flow patterns more accurately. Flow balancing proved extremely difficult by these methods. Unless one is willing to install flow measuring devices at each valve it is impossible to determine what the flow is and therefore to know what a particular valve setting should be.

During the latter stages of the project a reverse return plumbing system was installed on the ground array. Also, each parallel

cluster of collectors was modified so they would contain equal numbers of collector panels. This modification helped equalize head loss within each cluster thereby aiding balanced flow. Thermography studies conducted before and after these modifications showed significant improvement in flow equalization conditions.

As a result of experience gained on this project, reverse return piping on all collector arrays is definitely recommended. This arrangement forces the heat transfer fluid to travel equal distances and practically assures balancing of flow through all collectors. The cost of the additional piping is considered relatively minor compared to the loss of return in investment associated with an array which is operating inefficiently.

A great deal of experience was obtained during the course of this project regarding installation of plumbing. The comments which follow represent a compendium both of lessons learned and ideas which could prove useful regarding this important topic.

Piping layout should be as simplified as possible, e.g., avoid sharp bends, elbows, complicated reducing/expansion schemes, etc., as much as possible. This will not only tend to reduce head loss (and thus parasitic pump power) but will also reduce chances for future joint leaks.

Although a properly designed and operated system will not require frequent draining and recharge, the following recommendations should aid in accomplishing this task. All straight runs of pipe should be pitched to aid thorough draining of the system. Drain and fill valves should be located accessibly on collector arrays and also in interior locations if hydraulic conditions permit. Incorporation of drain/fill capability from interior space can be most beneficial, particularly when

roof arrays are involved. (Invariably, draining may be required during the worst weather of the year when roofs are their most hazardous.) Easily accessible fill/drain locations will also facilitate routine collection of working fluid samples for analysis. One cautionary note must be mentioned; any interior drain valves that could be reached by children should be installed with tool operated valves only and should not be threaded. (Threaded outlets provide the opportunity for mistaken connection of hoses, etc.) Petcock vacuum relief vents should be provided at collector high points to aid draindown. Isolation and drain valves should also be designed to allow partial draining (or bypass) of collectors within arrays for maintenance.

As mentioned previously in this report, accumulation of air in liquid collector systems can be a major problem. Provision of automatic air vent valves in all plumbing is therefore recommended as a good investment. Accordingly, when pipe direction goes from horizontal to vertical downward, an air separator and vent valve should be installed as well as at high points in the system.

This project utilized type K and L copper tubing and all three types of joints in use for copper piping, soldered, threaded and flared. Although hard soldered joints are normally recommended, no problems with threaded and flared joints were encountered. A good quality solder should be used (do not use 50/50 tin/lead solder) and "silver" solder is strongly recommended for use with evacuated tube or other high temperature type collectors.

The system should be pressure checked using the intended working fluid, not just water. This project used water and ethylene glycol which will leak where pure water will not. (This installation encountered this problem which necessitated crews coming back to the

job site.) Expansion tanks and gauges should probably be removed before pressure testing since those components could be damaged. After testing, the system fluid should be drained into a container. This will permit exact determination of the system's capacity, thereby facilitating the calculation of glycol amounts needed to maintain desired mix concentrations. (If the fluid used has no color, introduction of a dye should be considered to aid in detection of future leak locations.)

When charging the system prior to start-up, either the collectors should be covered or charging must be done in the morning. If these precautions are not taken, vapor locking of collectors is likely to occur and recharge may be necessary.

Plumbing to collector arrays should provide for pressure relief. The pressure relief valves should be placed at or near the collectors themselves since higher localized pressures are likely to be located there. Pressure relief systems should drain to a visible location in order to aid the detection of the venting. This project used a visible, translucent tank. Vented fluid should not be permitted to come into contact with roof material, or drain to other locations that could create a hazard or damage potential. The relief valve should also be plumbed so as to prevent its inadvertent isolation by other valves.

Although never used on this project, it is highly recommended that flow visualization site glasses and thermometers (or thermometer wells) be provided on key plumbing circuitry in solar installations. If control and/or electronic sensors fail, the presence of these manual checks on operation would greatly aid troubleshooting and repair. Another similar recommendation involves installation of shutoff valves to isolate components that may need replacement (e.g., temperature sensors, etc.) Replacement can then be made without the necessity of completely draining and recharging the system.

An automatic water makeup system to collectors should not be used; a water makeup system, however, probably should be included. A makeup system allows simple recharging procedures and provides for easier removal of air from collectors if they do become vapor locked. Backflow preventers must be included to prevent possible contamination of potable water with collector fluid. It bears repeating, however, not to allow the makeup system to operate automatically. If it is, and a system leak develops in winter, the ethylene glycol concentration will decrease and freeze protection will be lost. (This situation was inadvertently allowed to occur on this project; one collector became frozen before the leak was noticed--all could just as easily have been lost.)

Care should be exercised to prevent corrosion to collectors and other plumbing components. Dissimilar metals should be joined by dielectric unions, and corrosion inhibitors should be used in the working fluid. These precautions were taken on this project and no significant corrosion of collectors has occurred. (A collector which had been in service for two and one-half years was checked and was in good condition.)

This project has experienced flow blockages from foreign material present in the storage tank water as a result of mineral and corrosion deposits breaking loose from heat exchangers. Accordingly, fluid strainers should be installed in easily accessible locations, ahead of pumps, on all circuits. They should be isolated by shutoff valves to prevent the necessity for system draining when they are cleaned.

Energy loss due to thermosiphoning from heated storage water to collectors initially occurred on this project. Installation of spring-loaded check valves effectively controlled this potentially serious problem. Their use is definitely recommended.

Expansion tanks are required in collector piping to allow for expansion and contraction of the working fluid. Since most expansion tanks are provided with an air separator and vent valve, their placement at or near the collector array is probably beneficial. An air-chargeable, rubber diaphragm tank designed for 30 psig pressure was used on both arrays of this project. Although some authorities have recommended not to use rubber diaphragms for glycol-based fluids, no leaks have been encountered with these units in nearly five years of operation. It may be advisable, however, for designers to specify a non-rubber material such as neoprene if glycol fluid mixtures will be used. The tank should be placed on the suction side of the pump.

Pump selection and sizing is an important facet of design. Overdesign of pumps will lead to increased parasitic power requirements and decrease system efficiency. Single-stage, in-line, steel impeller and cast iron housing centrifugal pumps were selected for this project and have performed well. Seal leak problems with the glycol-water working fluid have been insignificant. A durable, good quality pump should be installed on collector loops since their failure could conceivably result in collector stagnation and subsequent damage. Pumps should be located in an easily accessible location and be provided with isolation valves to facilitate maintenance. They should also be placed on a separate electrical service line. This project utilized a separate switch on each pump to allow manual override of the control system. This feature permitted easy shutoff of a pump if the control system had malfunctioned and was forcing a pump to run when it should not have been (e.g., collector arrays operating at night, etc.). It is recommended that this cheap innovation be used for all projects.

Energy losses from piping can be significant and should be minimized by insulation. In the initial design of this project all lines were to be completely insulated with sleeve type elastomeric materials. Cost became a consideration, however, and the project was redesigned as follows: (1) Underground piping was insulated with hydrophobic type powder; minimum thickness was 3" below, 2" between, and 4" above the pipes. The top of the powder was covered with polyethylene sheeting to aid in moisture prevention. (2) Above ground piping on the arrays, although covered by sheet metal flashing, received no insulation. (3) Interior piping in the basement and exterior piping to the roof array was insulated with one inch thick, preformed, fiberglass sections.

In retrospect, if cost considerations become dominant, insulation on interior piping should be sacrificed ahead of exterior mounted pipes. Any losses which occur from interior piping will effectively become energy gains to the structure; not so, of course, for exterior pipes.

Subsequent thermography testing on the exterior collector plumbing proved that significant energy loss was occurring. These pipes were later insulated by stuffing standard rolled fiberglass insulation around them and under the sheet metal covers. Thermography showed practically no energy loss after this action. This solution, however, did not prove effective over extended time periods. The sheet metal covers were not watertight and allowed moisture intrusion. The fiberglass became wet and compressed and therefore lost much of its insulating value. Elastomeric or fiberglass pipe insulation is therefore recommended.

The powder insulation used on the underground piping was deemed to be effective. It is unknown if it has degraded significantly

but an indication of its continued effectiveness was given by the following observation: In the fall of 1979 (over four years after installation) a temporary plumbing modification was made which permitted thermosiphoning to occur from the storage tank to the ground array. The supply pipe at the entrance to the ground array (over 50 feet from the storage tank) became very hot by morning. This indicated that the insulation was still effective enough to prevent the thermosiphoned energy from being absorbed by the surrounding earth. Although an earlier section of this report recommended a more conventional insulation method for underground piping (see page 2-8) it is believed that hydrophobic powder represents a viable alternative, particularly if groundwater problems are not of major concern.

In summary, exposed piping should be insulated. DOE currently recommends that all piping should be insulated to at least R-4 levels. It should be stated again that care in initial layout to minimize pipe runs will pay great dividends in reduced energy loss and piping and insulation costs. Layout should, of course, provide adequate room for the specified insulation.

To conclude this section on plumbing appurtenances, a final word regarding maintenance considerations is offered. All valves, pumps, gauges, thermometers, etc., should be clearly labeled and tagged with typical operating data. A schematic of the complete plumbing system should also be provided in a visible location to aid maintenance crews. The reader is referred to subsequent sections of this chapter on Homeowner and Maintenance Manual Development for further information regarding this recommendation.

2.2.2.7 Evacuated Tube and Flat Plate Collector Comparison

Beginning on 1 October 1978 the ground array was equipped with evacuated tube collectors (Model TC-100) manufactured by General Electric. Because of these collectors' high cost ($20 per square foot FOB) only part of the support array was utilized, 17.8 square meters (192 SF) vs 25.4 square meters (273 SF) for the previously installed flat plates. The 52^{o} inclination angle of the array was not changed in order to permit direct performance comparison with the formerly installed flat plate collectors and also with the existing flat plates which remained on the roof array.

Evacuated tube collectors reportedly achieve higher efficiencies thereby allowing smaller collector areas (which will lower the cost of support structures) for a desired energy output. In addition, their vacuum "thermos bottle" design permits higher temperatures to be attained which allows smaller storage volumes, heat exchangers and other system components. For these reasons manufacturers claim that although collector costs are higher than for flat plates that evacuated tubes are cost effective.

Another principal advantage claimed for vacuum type collectors are that they will significantly outperform flat plates in marginal conditions. For example, they should operate on days when flat plates won't, start operation earlier and stop operation later in the day, etc.

The following conclusions regarding the vacuum tube collector performance are based on one winter of operation. These conclusions should be tempered with the understanding that the collectors were integrated into an existing retrofit solar application which was not designed to take advantage of the unique features attributed to them (e.g., it did not

require high temperature collector fluid, it possessed larger storage volumes than recommended for evacuated tubes, etc.).

The TC-100 collectors operated at an average instantaneous efficiency of only 25 percent, whereas the flat plates on the roof operated at 38 percent for the same period. Since the ground array had generally operated at higher efficiency (i.e., when both arrays used flat plates) this drop in efficiency was attributed solely to the evacuated tube's performance.

The evacuated tube collectors would try to begin operation sooner in the day than the roof flat plates but system cycling would occur. The tube collectors would remain on at generally the same time as the flat plates would start operation. Contrary to expected performance, however, was the fact that the evacuated tubes would shut down earlier in the day than the flat plates.

Another drawback to the tube collectors was their increased maintenance requirements. A few tubes broke during both normal operation and recovery from stagnation conditions. Their replacement, though not technically difficult, proved to be a time-consuming irritant. Numerous collector plumbing leaks were also initially experienced when stagnation conditions occurred. These occurred in the small 1/4 inch serpentine elbow and tee connections despite the use of a 70 psi pressure relief valve on the array. Subsequent repair of these joints with "silver solder" (standard solder had been used during installation) prevented recurrence of this problem. Accordingly, higher quality material and workmanship must be used in their installation.

Very little evidence is available to support the view that vacuum tube collectors outperform flat plates under marginal conditions.

The ground array did not operate any day in which the roof array didn't. It was mentioned previously that the vacuum tubes would also shut down earlier in the day.

To summarize, the evacuated tube collectors did not perform as well as the flat plates in this application and location. By contrast, the flat plate collectors have performed very well. No glass cover breakage has occurred despite frequent and sometimes extended stagnation periods. The only negative aspect experienced throughout the project was some minor outgassing and surface deterioration of the absorber plate of one or two collectors. This occurred during installation before the collectors were charged. Proper installation procedures would have prevented this occurrence. Accordingly, the flat plates were reinstalled on the ground array in the fall of 1979 prior to the termination of the formal research project.

2.2.2.8 Collector Cover Removal Effects

The evacuated tube collectors used in this project were available with an optional cover for hail and vandalism protection. Since the Academy has a relatively high risk of damaging hailstorms, covers made of Lexan® were installed.

These covers provide no added insulation for collector efficiency improvement, but were observed to provide a flat sliding surface for more rapid clearance of snow. This is particularly true for our installation which used an east-west tube orientation since the tubes and vee troughs impede the removal of snow. The tubes themselves do not radiate much heat which would tend to melt the accumulated snow.

The manufacturer's specifications predicted a 15 percent efficiency loss for collectors utilizing protective covers. It was decided to test this estimate by removing all covers from one cluster of

the collectors and comparing their performance to the other collectors which remained covered. Analysis of data over a three-week period in March 1979 confirmed this prediction. What had been the worst performing cluster became the highest, and reflected a 10-15 percent relative increase in collector efficiency.

A coverless collector was exposed to a short duration hailstorm. No breakage to the evacuated tube glass shrouds was experienced (the hailstones were 1/2 to 3/4 inches in size).

In conclusion, the added expense of the Lexan® covers (approximately $900 of the total evacuated tube collector cost of $5000) would not appear warranted in most applications. In those areas where severe storm damage or vandalism is of major concern it would seem advisable to use a much lower cost material for the covers. If cheap covers are not available from the collector manufacturer, then "site built" modifications would appear warranted.

2.2.3 Thermal Storage Systems

All solar heating installations require a storage system. For liquid collectors a water tank is generally the storage system employed. When providing for energy storage the designer is immediately confronted with choices concerning tank type and placement.

2.2.3.1 Tank Type and Placement

Tanks should be placed close to collector arrays and to the load side outlets. Aesthetic concerns in a residential neighborhood and the desire not to utilize space available to occupants in the basement led to an exterior, underground tank being used for this project.

Either steel, fiberglass or concrete tanks can be used. Based on initial cost alone, a reinforced concrete tank (4000 psi,

28 day strength) was selected and obtained from a local source. No interior water sealant was used. Shortly after start-up, the tank began to leak at the rate of approximately one gallon per hour. The tank was pumped dry and inspection revealed no observable cracking or leak locations. The tank was refilled and no further significant leakage has occurred since that time. No definite explanation for this occurrence is known. To preclude such leaks from occurring it is recommended that concrete tanks be lined with watertight material. The liner should be heat resistant since high storage temperatures will be encountered.

A device that allows easy monitoring of the water level should be used on all tank installations. A site glass could be used on some tank placements; this project used a manually operated float meter which was placed in the basement near the pumps and other solar equipment.

The tank sides and top were insulated with two one-inch layers of polyurethane (approximately R-13) which was applied with hot tar. The bottom of the tank was not insulated. It is felt that this degree of insulation was not sufficient. This conclusion is based on the presence of what was considered to be too much temperature/energy loss from the tank during severe conditions.

In retrospect, it is felt that the tank should have been supported on "thermal break" blocks with insulation on the bottom as well as the sides. The blocks would support the tank and prevent crushing of the bottom insulation. DOE recommends that underground storage tanks be insulated to R-30 levels, so it would appear that this project's design was inadequate in this area. Designers should insure adequate amounts of proper insulation are used to prevent excessive thermal energy loss from storage.

In sum, no significant, long-term problems were encountered as a result of using a concrete tank. Their use in new construction where they can be easily formed and poured in place (perhaps as part of foundation walls) may also have additional cost benefits that should be considered.

2.2.3.2 Storage Mass Variation Effects

This project used a tank capacity of 9500 liters (2500 gallons). The tank was almost filled to capacity during the first winter of operation. In July 1976 the storage mass was reduced to approximately 6800 liters (1800 gallons). This mass reduction had the immediate effect of making the storage tank more responsive to the energy input from the collector arrays. In short, for a particular environmental condition the tank temperature would rise much more quickly and to a higher level for a given energy input. This was very significant since during the first winter it was not unusual for the collectors to operate all day but the temperature of the storage water would not be raised high enough to use for home heating.

During the third winter of operation the storage mass was further reduced to 5300 liters (1400 gallons). Predictably, the tank again became more responsive to the higher temperature collector fluid. It should be pointed out that these storage mass reductions worked in combination with the reduced collector flow rates discussed previously to lower collector efficiency. (Higher storage temperatures result in elevated collector fluid and plate temperatures and consequently more thermal loss to the environment.) This sacrifice in collector efficiency was once again made to achieve higher system efficiency.

The final storage mass of approximately 5300 liters (1400 gallons) was the lowest achievable due to plumbing limitations. This amount

represents a storage mass to collector area ratio of approximately .88 kilograms per square meter (2.5 gallons per square foot). This ratio is within the general limits recommended for most flat plate collector systems although some studies indicate lower ratios are better.

To conclude, storage is the system component which connects energy collection to the load. Consequently, storage mass has an effect on collector efficiencies but more importantly on system heating efficiency. Lowering of collector flow rates and of the storage mass is believed to have been primarily responsible for the continual improvement in solar performance during the first three winters of this project. (See Section 2.5 for a performance summary.) It is further believed that storage mass reductions were the dominant factor in achieving these improvements. The designer is, therefore, cautioned not to use too large a tank. Excess storage volume costs money and delays the storage mass from reaching usable temperature levels.

2.2.3.3 Usable Temperature Levels

A parameter which is very closely related to storage mass is the minimum temperature at which it can be used to supply energy to the load. Initially, the control system required a 41°C (105°F) temperature in the storage water. This temperature resulted in approximately 31.5°C (88-89°F) air being produced at the distribution registers in the home. The storage tank spent considerable periods at 40.9°C (104°F), but the control system would not command withdrawal of this energy from the tank. In an attempt to use this significant amount of lower temperature energy an investigation was made to determine the lowest usable temperature which would not result in discomfort to the occupants.

In December 1976 the control temperature was reduced to 34.4°C (94°F) and the occupants were advised to check for drafts, etc. No

adverse reports were made. The temperature was subsequently reduced to 32.2°C (90°F) and then to 30°C (86°F). The lowest setting resulted in 26.7°C (80°F) air at the registers. The installation of linear diffusers at all registers prior to these latter reductions is believed to have helped prevent any occupant complaints. (The last two reductions were made without informing the occupants.) It is true that the occupants were an active part of the research project and could have had a natural inclination not to make complaints. However, the home has remained comfortable in the solar heating mode with this lower temperature setting to the present "nonresearch" occupants.

This lowering of the storage tank control temperature, in conjunction with the reduction in storage mass, aided tremendously in the improved overall performance of the solar system. It should be remembered also that the placement of the storage tank sensor, as well as the control temperature chosen, can have a significant impact on system performance. (More will be said about sensor placement in the succeeding section of this chapter.)

2.2.3.4 Heat Exchanger Interface

Two flat, steel, serpentine flow path (ca 29" x 59") heat exchangers were placed in the storage tank and connected to each collector array flow circuit. The heat exchangers were plumbed in parallel on both array circuits. These four heat exchangers were considered necessary to avoid using ethylene glycol in the storage water to the same concentration required in the collector fluid.

During the first winter of operation it was noticed that a fairly significant difference existed between the storage water and the collector entry fluid temperatures. It was therefore decided to add a third, identical heat exchanger on the ground array loop to see if

it would reduce this temperature differential and thereby improve the transfer of energy from the collector fluid to the storage water.

The addition of this third heat exchanger resulted in a reduction of the ground array average working fluid temperature. The temperature difference imparted to the working fluid by the collectors (entry vs exit) remained the same but the entire loop tended to more nearly approach the storage tank temperature. This resulted in the ground array collectors running cooler, and therefore more efficiently, than the roof array.

Another effect of the additional heat exchanger was also noted. The ground array collectors would shutdown approximately 15 minutes earlier in the afternoon than the roof array. The control system's shutdown mode was based on a pre-set differential between the collector fluid exit temperature and storage temperature. Since the ground array loop was now running cooler it would reach this differential sooner and begin shutdown. This does not necessarily imply reduced performance.

Heat exchangers should be plumbed to allow use of the entire storage tank volume. Their placement should also take temperature stratification potential into account. When it was decided to reduce the storage mass in this project it became necessary to disconnect and lower the heat exchangers in the tank. Similarly, further reduction of tank mass below present levels would require yet another plumbing hookup. The use of flexible hose connections might be considered in order to provide flexibility of heat exchanger placement in the tank.

Corrosion and mineral scale deposition on the exchangers has occurred in this installation. Dielectric unions were used between the copper piping and steel exchangers and were deemed effective in preventing galvanic corrosion. Uniform, exterior corrosion on all exchangers was the

main problem. Inhibitors were never added to the storage tank water but their use may be warranted and should be considered.

The hardness of the storage water decreased which indicated that precipitation of calcium and magnesium salts did occur on the heat exchangers. Mitigation of this problem could be realized through use of softened or dionized water for storage, but this could be too expensive or not deemed feasible.

The designer must be cognizant of the corrosion and scaling potential for the storage tank heat exchangers. This consideration, along with the need to achieve maximum energy transfer to storage, probably makes a liberal approach to heat exchanger sizing advisable. An investment to insure adequate heat exchanger capacity is probably minimal compared to the loss incurred by a relatively high cost but inefficiently operating collector array.

2.2.4 Microprocessor Control Systems and Sensors

An efficient solar system must have reliable control and sensoring components. This section will be restricted to recommendations and lessons learned regarding hardware; discussions concerning the control algorithm or logic used in this project are found in previous sections.

In general, there are two fundamental types of control systems which can be used for solar systems. The first, and more common, is an electromechanical relay system; the second uses solid state, integrated logic circuits in a microcomputer or microprocessor. This project used a microprocessor-based control system during the entire research period. A simplified, "mini-microprocessor" was also designed, built, and installed in the home prior to its turnover for normal occupancy.

Microprocessor controllers proved to be very feasible for this project. They are small, lightweight, consume negligible power and have the capability to implement new control algorithms or strategies easily. This latter characteristic is considered to be an important advantage for these types of controllers. Their only disadvantage, as compared to relay type controls, is that they are not as well understood by most engineers, contractors or maintenance personnel. This is a very real concern that should be given much consideration by Air Force designers.

The solar system controller, of necessity, also controls the auxiliary heating system. This means that a potential exists for a malfunctioning solar controller not to be able to activate the backup heating system. A feature of the control scheme used in this project involved by-passing the normal thermostat which activated the auxiliary furnace system. The conventional thermostat is always at a lower setting than the desired interior temperature used on the solar controller thermostat. Operation in this manner helps assure that a malfunctioning solar system will become immediately apparent to the occupants. Stated simply, if the solar system (or solar controller) malfunctions, the house will probably get cold. The occupants can then call for maintenance assistance. Until repairs are made, the conventional thermostat can be raised to the desired level and the home is heated solely by the auxiliary system just like any other house. It is recommended that a similar control strategy be used for other projects where applicable. There have been cases reported where occupants of solar facilities thought the solar system was functioning normally when in fact it wasn't functioning at all. Control hardware should be designed and installed to help avoid this situation.

Another unique feature of the mini-controller used in this project is its use of a display cover panel which depicts system operation. This display panel reflects what the controller is telling the system to do, e.g., if the panel's collector array pump light is on, the pump should be running. If the pump is not running, then either the pump or the controller output signal has malfunctioned. Similarly, if the collector display light is on when it shouldn't be (e.g., at night) then the occupant knows that the controller has malfunctioned. Simplified figures of this display panel with explanations of common operating modes were provided to the occupant. It is felt these measures help to achieve a system which will operate and operate correctly.

The system controller should be installed in an easily accessible and visible location. This is particularly true if an operational display panel is used. The controller should be ventilated well since internal power supplies can overheat some of the solid state components and cause them to fall. Lightning protection devices should be installed on sensor inputs to the controller. The controller should also be placed on a separate electrical circuit to preclude possible overloading and a potentially damaging shutdown of the solar system.

One final innovation incorporated into this project's control system was the provision of manual toggle switches (powered by a flashlight dry cell battery) to control all pumps and fans. This manual system allows maintenance forces to operate all system components independently of the automatic controller. This low cost feature allows much easier troubleshooting of the system and facilitates routine operational checks. It is recommended that this, and the previously discussed innovations, be used in other solar projects.

The sensors used in the AFA solar home were solid state temperature transducers. They are very accurate temperature sensors, and when installed properly, they have performed very well. Accurate indications of temperatures are important to system performance; a significant error in temperature measurement will almost certainly result in a significant impact on system performance. It is recommended, therefore, that accurate, high quality sensors be specified.

Based on the experience gained in this project, it is felt that a control scheme which is simplified as much as possible performs as effectively as a more sophisticated approach. The simpler the control algorithm, the fewer the number of sensors required. The final configuration of this installation used only five sensors; they monitor the following system temperatures: collector plate, collector fluid exit, storage tank, actual interior and desired interior. Additional sensors are installed and serve as backups to the ones being used to control the system. It is recommended that redundant sensors be provided for relatively inaccessible locations such as collector roof arrays. As a minimum, adequate spare sensors should be on hand to support a replacement requirement.

Sensor location and the method of installation should be specified carefully. Improper location can degrade system performance significantly. If collector arrays will be partially shaded during certain times of the year, the collector plate sensor must not be mounted on the shaded area. It is recommended that the collector sensor be mounted on the absorbing plate and not on a return pipe near the absorber. (In this project it was necessary to cut into the back of a collector in order to properly install the plate sensor.) The collector sensor must be installed in a manner (screw clamps, thermal cement, etc.) which will insure good

thermal contact with the absorber plate. Collector plate sensors must also be able to withstand anticipated stagnation temperatures to preclude frequent replacements.

Storage tank sensor placement should take stratification potential into account. If it is located near where the collector fluid is releasing its energy to storage, the sensor may give erroneously high readings. This would result in shorter collection periods and would seriously affect solar performance. Since the collector loop heat exchangers were distributed evenly throughout the storage volume and the water was mixed by the heat coil pump, this project did not achieve much stratification. Accordingly, only one sensor was used; it was placed in the upper quarter of the storage mass. Frequent failure of the storage tank sensor was experienced early in the project due to its direct immersion in the water. Even though the sensor construction supposedly permitted immersion, the hot water would ultimately short-circuit the output signal. This problem was solved by enclosing the sensor in a copper pipe which was capped and sealed with silicon gel. It is felt that the sacrifice in temperature accuracy was minimal.

Sensors that are exposed to the outdoors should be covered to protect their electrical leads from moisture damage. This project used a small, site-fabricated, plexiglass box sealed with silicon gel.

All sensors should be placed in accessible locations and installed to facilitate easy replacement. Isolation valves are recommended for sensors installed in piping. This will allow sensor replacement without draining of the fluid system.

Good quality sensor wire should be specified since it may come in contact with very high temperature surfaces. All wire connections should be soldered since extremely low output signals are produced by the

sensors. (This project has experienced inaccurate readings due to connections that weren't initially soldered.)

To summarize, poorly designed and installed control and sensor systems can cause an otherwise well designed project to operate inefficiently. The majority of the routine problems which were encountered in this project were due to deficiencies in this area. It is hoped that the foregoing recommendations can help prevent similar experiences in other projects.

2.2.5 Thermography Studies

Thermographic equipment will detect and visibly display temperature distributions existing on a body's surface. The equipment senses the infrared radiation that is either being reflected or emitted by the surface.

Flow imbalances in the collector panels were a major concern in the early stages of this project. Even though pressure gauges and balancing valves were in use, it was decided to use thermography in an attempt to determine actual flow patterns. It was realized from the outset that the surface which the thermography equipment would sense was the glass cover plates and not the absorber surface. Reflected radiation and convection losses to wind from the glass, and other factors, all combined to cause some doubt regarding the ability of thermography to accurately portray absorber surface temperatures. Although it was recognized that actual temperature profiles of the absorber surfaces would not be possible, it was hoped that qualitative differences in absorber temperatures would be transmitted to the glass covers. The presence of temperature sensors on all absorber plates of the ground array allowed correlation of these readings to the qualitative thermographs which were taken.

The results of two years of experimental work with this technique proved its usefulness. Thermography unquestionably gives a reliable indication of collector flow balance, obstructions or air blockages. The effects of adjustments to flow balancing valves and bleeding of entrained air could be seen quickly through the thermography equipment.

It is felt that thermographic equipment can be best utilized during system startup (to achieve flow balance) and subsequent routine checks for flow blockages. Because of the cost of this equipment its use will probably be restricted to large collector arrays. The Air Force should add this application to its list of uses for its thermographic equipment.

In summary, it is believed that thermography represents a current and reliable method of accurately determining the gross operational effectiveness of solar collectors that are installed on a non-research project. Normal installations are not apt to possess the many sensors and flow meters which would otherwise be required to detect flow blockages and imbalances. The solar thermography research pioneered by this project in 1976 is being continued by the Department of Energy through its Solar Energy Research Institute (5).

2.2.6 Design Model Comparison to Actual Performance

At the time this project was planned, very limited solar design guidance existed. Since that time several computer design models have been developed. These models generally attempt to predict the solar energy contribution for a particular system size and application. This allows estimates of conventional energy savings and an economic analysis of the proposed solar installation to be made.

The "f-chart" model developed at the University of Wisconsin (6) is such a model. It is widely reputed to be the state-of-the-art in solar design techniques. It is specifically intended to aid in the sizing of standard, active (liquid or air), flat plate, space heating and/or domestic hot water systems. The model treats collector area as the main design parameter but also considers storage mass, heat exchanger efficiency and other variables. The model assumes a system of specified collector area to be optimally designed and operated. It is for this reason that the solar energy fraction of total consumption (i.e., "f") predicted by the model is often considered to be optimistic.

The f-chart model has been extensively compared to many other computer simulations and excellent agreement has been obtained. Relatively few actual projects that possess reliable data have had their performance compared to the model predictions. For this reason it was decided to obtain the latest computer f-chart model (version 3) to see what level of performance it predicted for this project.

The f-chart program is based only on use of flat plate collectors so the last winter of operation was excluded from this comparison. It was also necessary to delete other periods from the analysis if they involved considerable startup and operational experimentation (collector inclination angle changes, etc.) which resulted in less than optimum system performance. The period selected was September 1977 through August 1978. Table 2-1 shows a month-by-month comparison of the actual thermal performance of the home during this period to that predicted by f-chart.

Although individual months show considerable discrepancy, the total annual contributions are in excellent agreement. The actual performance in May and June are unusually low due to a severe spring snowstorm

MONTH	PERCENT SOLAR CONTRIBUTION	
	f-CHART	ACTUAL
September	100	100
October	89	100
November	57	67
December	44	61
January	46	34
February	53	50
March	59	66
April	74	89
May	92	47
June	100	56
July	100	100
August	100	100
Annual	59.7	60.8

TABLE 2-1. Comparison of Actual Thermal Performance to f Chart Predictions

and operational difficulties with the solar system. The total energy demand and solar contributions are so low for these months, however, that they do not significantly affect the annual performance.

The f-chart performance predictions are based on internally stored weather data (solar insolation and degree days) for nearby Colorado Springs, Colorado. The program version used in this comparison contains stored weather data for over 300 locations throughout the country. It is believed that weather variances between a specific location and the nearest

data location probably represents the major shortcoming to the f-chart model.

The excellent annual performance agreement obtained for this project indicates that the f-chart model is a valuable design tool. It is therefore recommended that this model be used by the Air Force to support preliminary design studies for solar space heating and domestic hot water projects. Recommend the Engineering and Services Center provide design suggestions based on f-chart predictions to individual bases that are considering solar projects.

2.2.7 "Homeowner" Manual Development

Prior to termination of this research project and turnover of the home for normal occupancy, it was considered necessary to prepare a simplified manual for a typical homeowner. It was felt that an occupant who had some knowledge of the system's operation would not needlessly call for maintenance forces. In addition, a homeowner familiar with the system can help insure that the system is, in fact, operating and operating correctly.

The manual appears in its entirety in the final interim technical report (4). The content of this short manual (9 pages) is briefly summarized as follows: An introduction informs the occupant of typical solar performance. It is written in a manner which will, hopefully, foster a positive attitude about living in a solar home, e.g., it points out that the occupants can contribute to the nation's energy goals.

A general overview of the solar system operation, in lay terms, is included. This will acquaint even the most nontechnical reader with how the sun is used to heat the home. A casual understanding of this

section, for example, will permit the occupants to know that collector pumps should not run at night, and other similar fundamental principles.

A short section advises occupants of the routine maintenance which the system requires, and when civil engineering forces are scheduled to accomplish it.

The heart of the manual is closely tied to the solar controller's visual display panel (see Section 2.2.5). It is believed that the manual's descriptions of the various operational modes which are displayed on the controller will greatly aid a homeowner's understanding of the system. In effect, the concerned occupant can "troubleshoot" the system himself. Examples of these operational mode descriptions are shown in Figure 2-1.

In summary, it is strongly recommended that facility occupants, particularly residential "homeowners", be furnished with information describing "their" system on all solar projects. This recommendation also applies to commercial package systems that may be installed by contractors. Provision of this information will greatly aid the continued successful operation of a solar system.

2.2.8 Maintenance Manual Development

This project's solar system was maintained primarily by the research team with assistance by base civil engineering forces on a case-by-case basis. Although the system does not require extensive or frequent maintenance, it was nevertheless believed that civil engineering should be provided with an operation and maintenance manual when the house was returned to their control for normal occupancy.

The manual appears in its entirety in the final interim technical report (4). The following paragraphs briefly summarize the contents of it.

● Display Light On

○ Display Light Off

MODE 2

SOLAR CONTROLLER

○ Gas
○ Tank Pump
● Ground Array
● Roof Array
○ Fan
○ Activity (Blinking)

Both collector array pumps on. Sun is shining and solar energy is being collected and transferred to storage tank water.

MODE 4

SOLAR CONTROLLER

○ Gas
● Tank Pump
● Ground Array
● Roof Array
● Fan
○ Activity (Blinking)

Mode 2 and Mode 3 comments apply.

MODE 3

SOLAR CONTROLLER

○ Gas
● Tank Pump
○ Ground Array
○ Roof Array
● Fan
○ Activity (Blinking)

Storage tank pump and fan are on. Hot storage tank water is being pumped through the furnace heat exchanger; therefore the home is being heated by solar energy. Sun is not shining, however, and collectors are not operating.

MODE 5

SOLAR CONTROLLER

● Gas
○ Tank Pump
● Ground Array
● Roof Array
○ Fan
○ Activity (Blinking)

Mode 2 comments apply. The home is being heated by the gas furnace since the temperature of the storage tank water is not high enough to provide the necessary energy.

Figure 2-1. Homeowner Manual Descriptions of Solar Controller Display Panel

Considerable attention was given to collector operation. Complete flow diagrams showing locations of all pumps and valves, detailed draining and recharging procedures and maintenance of proper ethylene glycol concentration in the working fluid are all discussed. Since collectors represent the major portion of a solar project's cost, it is important that continuing attention be given to them.

Repair instructions were also given for the solar controller and installed sensor system. A control diagram showing exact locations of all sensors and a wiring diagram of the system was included. Since it was felt that very little knowledge regarding solid state controllers is possessed by civil engineering craftsmen, detailed checklist instructions were developed to aid troubleshooting of this key system component.

Other routine tasks of a more mundane nature were also itemized. Cleaning pipe strainers, checking pump couplers and pressure relief valves, etc., are requirements which should be accomplished on a scheduled basis. These and other preventive maintenance items should all be entered into the civil engineering recurring maintenance program. Commercial equipment specifications (e.g., for collectors, sensors, expansion tanks, etc.) were included as appendices to facilitate ordering of necessary replacements.

Solar applications in the civilian sector have too often been the victim of an "install it and forget it" mentality. Active solar systems can't be forgotten about if they are to provide extended service. As a trustee of public funds it is incumbent on the Air Force not to repeat these experiences. Although solar systems are <u>not</u> "high technology" or inherently difficult to maintain, they still represent a mystery to most craftsmen. It is not enough to simply enter one-line descriptions

of required tasks in a recurring maintenance schedule; a manual explaining why and how these tasks are performed must be available. It is strongly recommended, therefore, that all solar projects which will be maintained by Air Force in-house forces require the development of a maintenance manual for the specific system that will be installed.

2.3 Solar Performance

This project's solar system performed well. As noted in a previous section of this summary, the actual performance slightly exceeded that predicted by a widely used computer simulation model. The annual solar contribution to the total energy consumption of the home approximates 60 percent. This assumes that the system is reasonably maintained and that average weather conditions will exist. The system would not attain this performance during a climatically severe year.

Figure 2-2 is a graph depicting the average solar energy available to a horizontal surface during the entire research period. The graph displays nothing unusual except a slight downward trend of available energy throughout this period of record.

Figure 2-3 shows the heating degree days for the entire period. In general, it depicts a trend of increasingly severe winters throughout the period of record. ($^{\circ}$F-days are used since this unit will be more meaningful to most readers.)

Figure 2-4 shows the total energy used and the solar energy provided to the home. Note that the energy demand of the home follows the degree day plot fairly closely. The dramatic effect of the increased insulation (added in February 1977) can be seen by comparing the demand during March, April, and May 1976 to that experienced in 1977. Even though the degree days were equal or greater in those months in 1977, the energy demand of

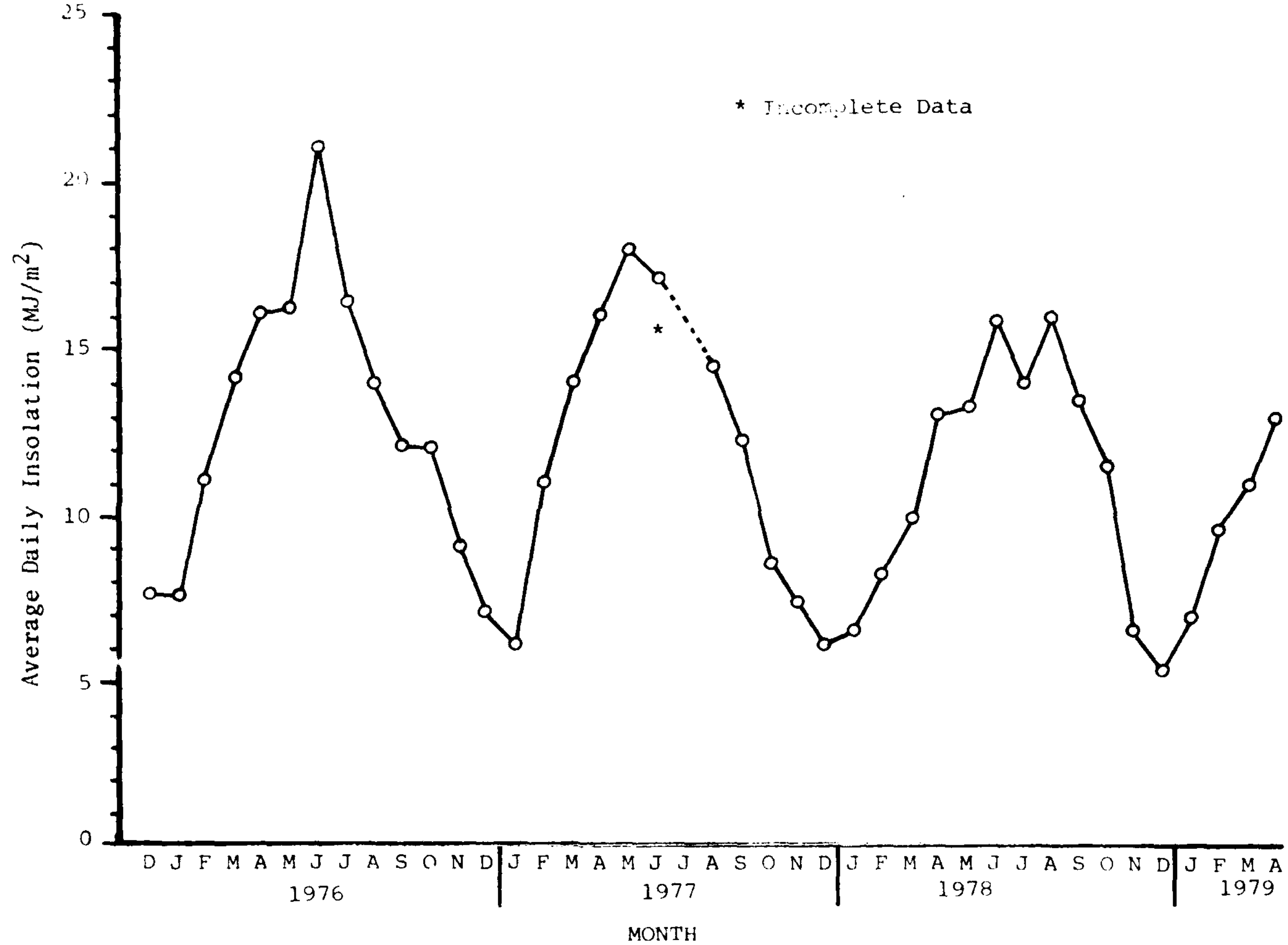

Figure 2-2. Total Energy Available

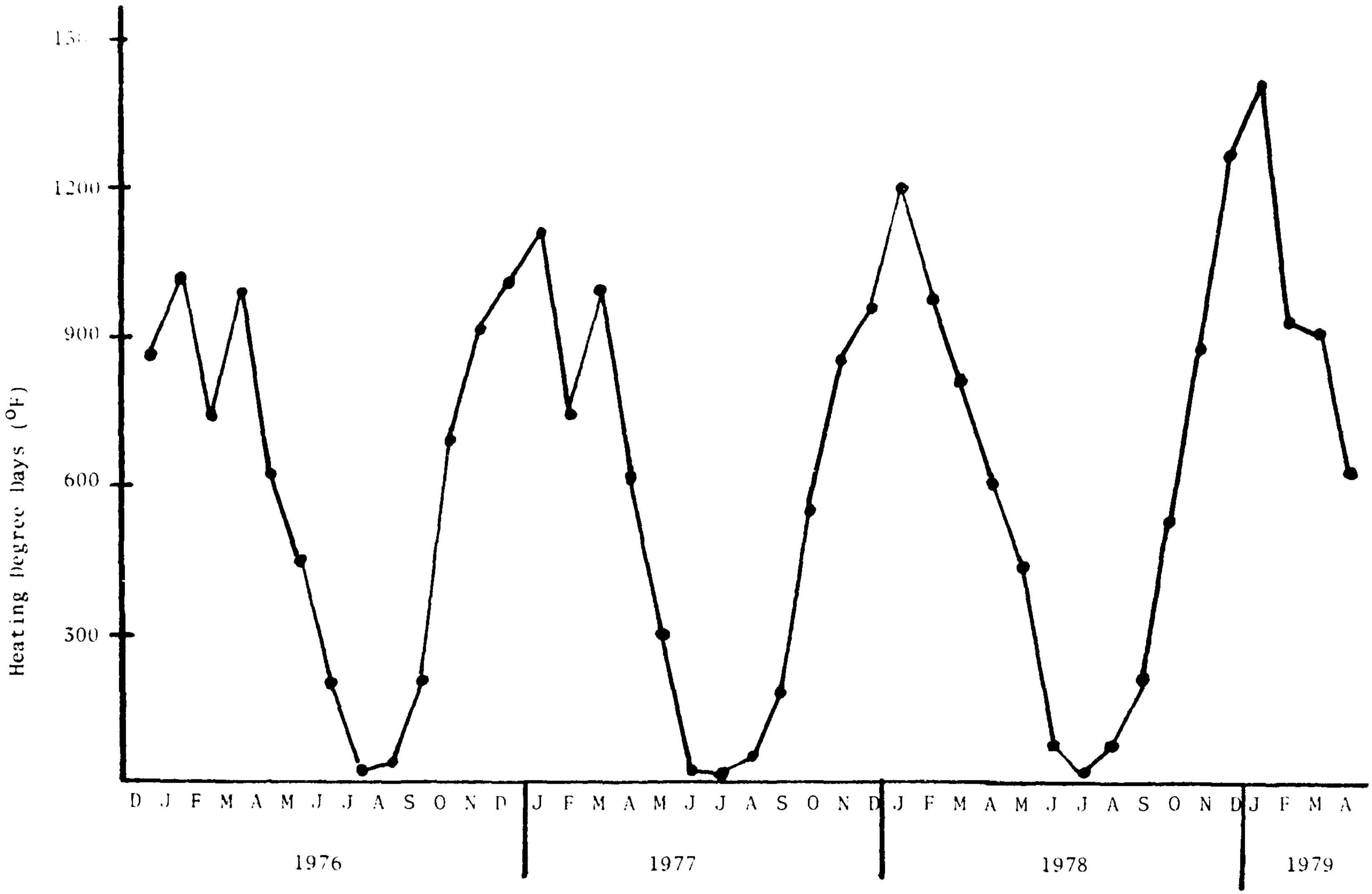

Figure 2-3. Heating Degree Days

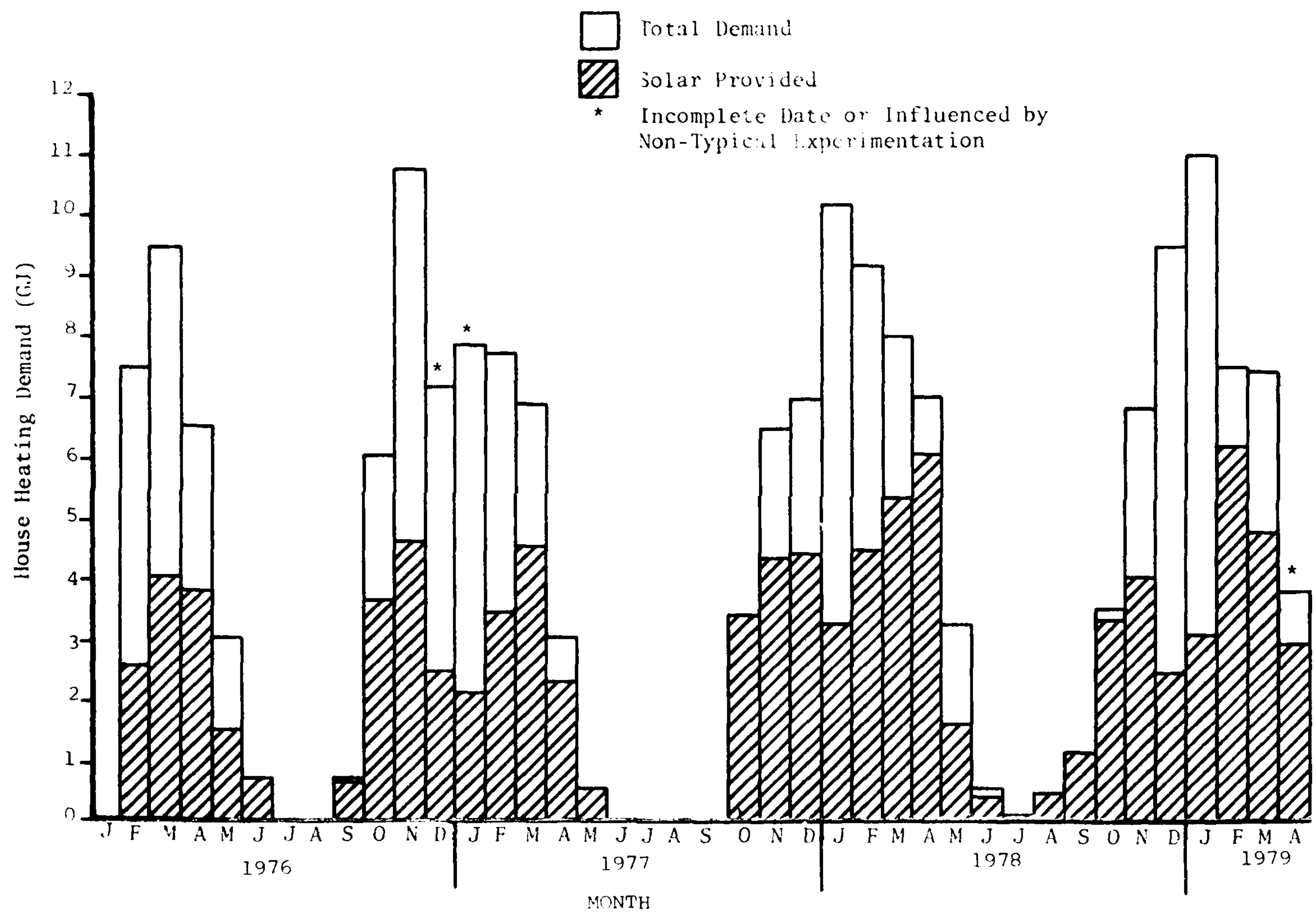

Figure 2-4. Total House Heating Demand

the home was greatly reduced. This reduction of the "demand to degree day ratio" continued until February 1978 when the home's energy demand increased significantly. This can be seen by comparing the months of March and April in 1978 to 1977.

The degree days experienced for those months in 1978 are significantly less or approximately equal to that for 1977, but the energy demand of the home was nevertheless much higher. The primary reason for this dramatic change was the fact that the home became unoccupied in January 1978. (It remained unoccupied for the duration of the research project.) It is believed that the energy gains associated with normal occupancy, which were never measured, are extremely significant in the total energy budget of a well-insulated, residential structure. The window blinds on the home were also closed while it was unoccupied. This prevented any solar gain from the low winter sun and could have contributed to the increase in demand.

Figure 2-4 also shows that the amount of solar energy provided to the home during the heating season (October - April) continually increased over the first three winters of operation. (Reliable data for the first winter exists for only half the season.) This improved performance occurred primarily as a result of operational improvements which have been previously discussed. The solar system continued to provide a large amount of energy in the last winter (78-79), but direct comparisons are difficult due to the lower-efficiency evacuated tube collectors which were installed on the ground array during this period. It must also be remembered that 30 percent less collector area was in use for the evacuated tube collectors.

Figure 2-5 gives a monthly "percent solar" summary. The data is typical of solar space heating projects. It reflects an average low of 30 percent solar for severe months to a high of 100 percent for low-load months.

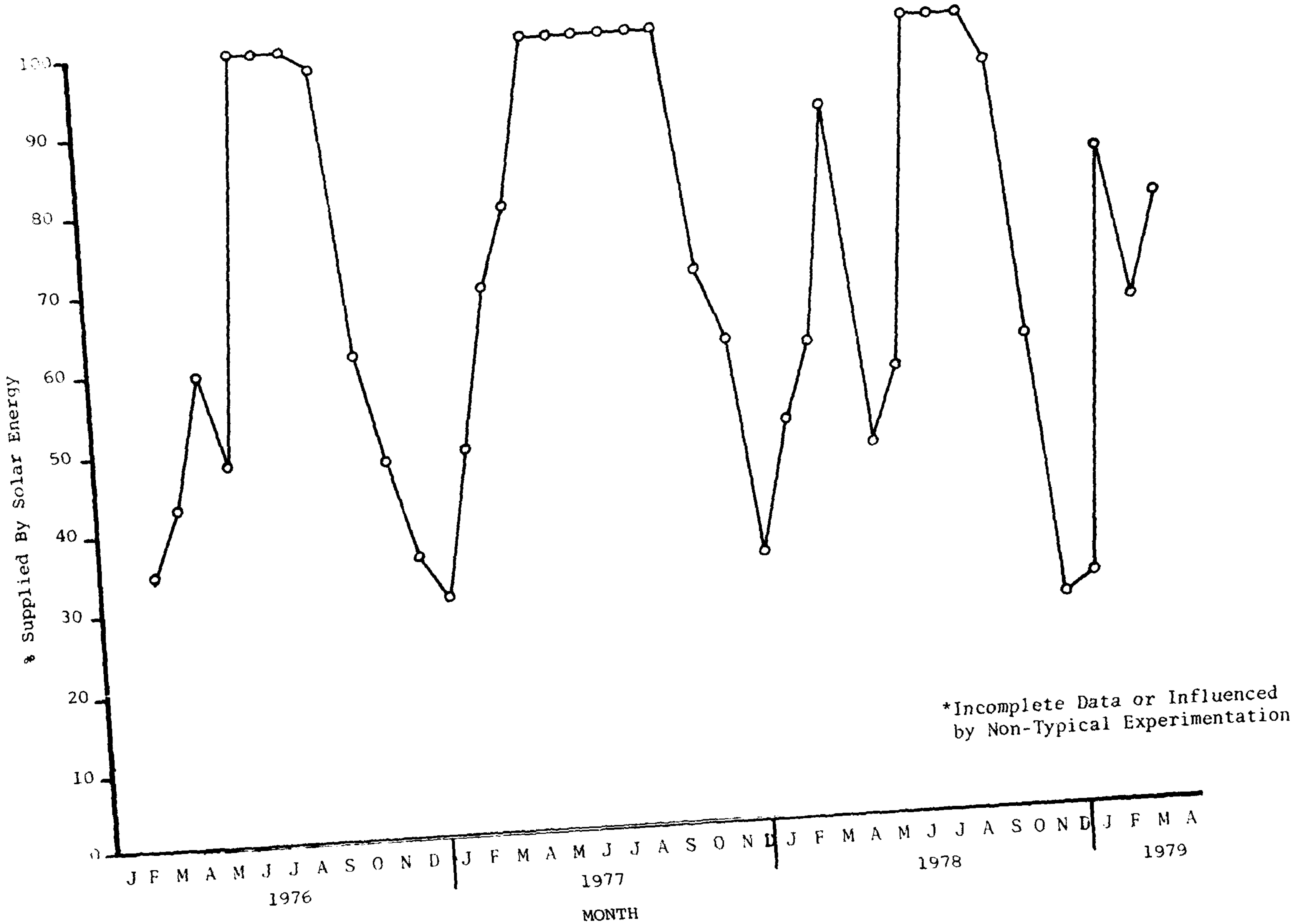

Figure 2-5. Monthly Solar Contribution

Time Period	1	2	3	4
First Winter (Dec 75-Apr 76)	52%	30%	21%	14%
Second Winter (Oct 76-Apr 77)	47%	40%	45%	19%
Third Winter (Oct 77-Apr 78)	35%	70%	61%	25%
Fourth Winter (Oct 78-Mar 79)	32%	65%	53%	21%

LEGEND

1: Solar energy collected and stored ÷ Solar energy available to collectors

2: Solar energy provided to house ÷ Solar energy stored

3: Solar energy provided to house ÷ Total energy demand

4: Solar energy provided to house ÷ Solar energy available to collectors

Table 2-2. Solar System Thermal Performance Summary

Table 2-2 summarizes the thermal performance of the solar system for all heating seasons of the research period. Data for October and November of 1975 and April 1979 were either nonexistent or too unreliable to use; their absence must be considered when comparing these results. The third winter of operation reflected the highest thermal efficiency and it is believed that the home in its current configuration and operational mode will approximate this level of performance.

Other comments concerning this table are as follows: In general, column one reflects the purposeful decrease in collector efficiency which was obtained by lowering collector flow rates. This led to higher temperature collector fluid and, in turn, to higher temperatures in the storage tank. The reduction in tank mass also contributed to higher and more usable temperatures in the storage tank. Column two reflects this increased usability of storage in providing energy to the home. The solar fraction of total energy provided is shown in column three. Column four can be regarded as the overall thermal efficiency of the solar system, i.e., the ratio of thermal energy provided by the system to the solar energy available to the system. The decrease in this overall performance during the final winter of operation is mainly attributable to the evacuated tube collectors which were installed on the ground array.

CHAPTER 3

SOLAR ENERGY - SOME OBSERVATIONS AND RECOMMENDATIONS

3.1 Introduction

The contents of this chapter are not to be interpreted as ironclad conclusions and recommendations which must be agreed with or implemented posthaste. They, rather, are the opinions of the author and other members of the research team, past and present, regarding the status of solar technology and what it should do for the Air Force.

The observations which follow were formulated over a period of time by those who were directly involved in an operational solar retrofit project. As a result of this fortunate circumstance, we had the unique opportunity to observe installation, maintenance, and operational problems. (Most of the specific problems have been discussed in the preceding chapter.) We also had the opportunity to read much and to interface with other solar researchers. Sometimes we simply sat and watched solar "work", and other times we sat and thought about it. The following pages are a result of the latter activity.

3.2 Solar Implementation - Planning and Programming

Many topics can be discussed under this broad heading, but the following ones are considered most pertinent.

3.2.1 Education and Training

It is believed that solar technology, though much of it is not complex, is still regarded as a mystery by most Air Force civil engineers. This observation, if correct, presents a most important barrier to the use

of solar on a broad scale. It is critically important therefore that the Air Force support, to the maximum extent possible, design engineers' attendance at the myriad of conferences and seminars that are being held throughout the nation. These sessions are not necessarily confined to solar technology, nor should the interests of our people be so restricted. Many of the conferences are subsidized by other agencies of the government, and can be attended at very little expense to austere travel budgets. A basic impediment to base engineers' attendance at these functions is that they are simply not aware of them, i.e., they are not on the right mailing lists! It is recommended that appropriate personnel make the effort to be aware of all pertinent meetings in the nation and advise nearby bases of their availability and cost. As a hypothetical example, why should an engineer at Williams AFB, AZ, be sent TDY to the AFIT School of Civil Engineering for the Energy Applications Course if similar exposure could be gained at a technical short course or seminar at Arizona State University for less cost? We need to make ourselves aware of all available opportunities in an effort to get more "bang for our TDY buck".

A side benefit of such a strategy would be the contacts our engineers would make with others involved in energy technology in their geographic area. Our people ought to know, and be challenged by, what is being done outside their front gate.

The foregoing policy would not lessen the value of the AFIT School of Civil Engineering courses. They are excellent and should continue to be supported and perhaps expanded. The solar energy block of the Energy Applications Course is believed to be particularly worthwhile.

A final word regarding educational efforts is offered. The common problem of getting back to the base and forgetting most of what one

was exposed to, is particularly critical in solar technology. It is not enough to educate; we must provide a reasonable opportunity for engineers to actually design a solar project if we are to get a payback on our training dollars. More about this in the succeeding paragraph.

3.2.2 The "Showcase" Concept

There is a natural tendency to go as far and as fast as possible in the implementation and demonstration of a new and promising concept. This is probably particularly true for a concept as popular as solar and other alternative energy technologies. This tendency is manifested by development of showcase installations which use all available methods, some practical and others perhaps impractical, to demonstrate that aggressive action is being taken. Although much can be learned by such a strategy, it is felt that a broadly based Air Force-wide effort will pay equal, and perhaps greater, dividends.

Our available "energy dollars" should be spent on decentralized and, hopefully, practical projects. It has often been said that widespread application of solar energy is as much an institutional as it is a technological problem. The showcase strategy does not adequately address the very real institutional problem of acquainting most of our design engineers and maintenance craftsmen with solar systems. As stated in the preceding section, our training efforts will go for naught if our trained people do not have the opportunity to utilize their new knowledge.

It is recommended that we begin by having as many bases as possible design and install relatively small solar systems. (A $50,000 investment on a base could install 10-20 residential sized DHW systems.) We must design, operate, and maintain relatively small and simple systems if we ever hope to successfully implement higher technology solar systems

for industrial and other uses. Even if some of these small efforts are unsuccessful, they will teach much and probably hurt little. It is probably true that despite our best efforts there will be some "reinvention of the wheel", but it is believed that this an unavoidable consequence of widespread action. To learn by doing is probably the best and perhaps only method to overcome our organizational inertia and lack of expertise. In short, we must collectively crawl up the learning curve if we are ever to sprint.

3.2.3 Preferable Applications

Solar energy applications are generally classified under two broad categories--direct thermal use and solar generated electricity. Direct thermal use includes provision of domestic hot water and space heating, space cooling, and industrial process heat in the form of hot water or steam. Terrestial electrical generation can be achieved by photovoltaic "solar cells" or by thermal conversion processes. Examples of this latter method are steam production by concentrating "power towers" combined with turbines, or low temperature heat engines driven by solar pond "collectors". (Some would also include wind generators in the latter category.)

There seems to be little question that direct thermal applications are more developed and practical than the electrical generation technologies. Within the direct thermal use category, applications that operate on a year-round basis are more economical than seasonal uses. For example, residential domestic hot water (DHW) production is more cost effective than residential space heating. It is further generally acknowledged that space cooling, whether in small or large projects, is considerably less feasible than heating applications. (It is believed this is true even if a year-round cooling load existed.)

It is therefore recommended that the Air Force use its "solar dollars" to install the types of systems which are most nearly economical today. Residential DHW, dining hall hot water, and aircraft washstand systems should be widely installed before space heating, let alone space cooling projects are implemented. Residential DHW applications also fulfill the previously recommended criteria of being small "learning projects" for base engineering organizations.

Having given this advice, it should not be forgotten that at some bases return on solar space heating investments could be greater than that of DHW installations at other locations. Space heating and other solar applications should, of course, be pursued under those circumstances.

3.2.4 Economic Analysis

It is arguable whether or not even the most feasible solar applications (e.g., residential DHW) are cost competitive, Btu for Btu, with current conventional alternatives. The rationale for conversion is found in anticipated future price increases of conventional sources and in attempting to account for "social costs". (An example of social cost is our dependency on foreign imports.)

For these reasons government policy at national and state levels has adopted significant incentives for conversion to solar energy by the private sector. Current federal tax incentives provide homeowners a 40 cent rebate on every dollar invested up to $10,000. (Additional incentives are provided to businesses who install energy producing systems.) Many states provide additional incentives. As a dramatic example, a Colorado resident who installs a solar DHW and heating system for $10,000 will receive $7,000 back in tax rebates. In effect, the private homeowner

outside the USAFA main gate is basing his decision on whether the energy savings produced by the system will recoup his $3,000 investment.

It is believed that current Air Force project programming guidance takes no account of the solar subsidies available to the private sector. As a result, we will shortly find our installations lagging far behind our civilian counterparts if this imbalance in economic analysis is not somehow redressed. If it is national policy to foster conversion to solar technology it must also apply to federal installations. If Air Force Civil Engineering desires to remain in the forefront of engineering technology we should strongly recommend to appropriate officials that our decision-making criteria stay competitive.

3.2.3 Base Master Planning

All future facilities should be sited and oriented to take advantage of solar energy. This includes consideration of present and future solar access (i.e., right to sunshine) and placement of the structure to permit use of south facing mass walls and glazing. (More will be said later about passive applications of solar energy.)

The project booklets for new facilities should itemize basic solar concerns. For example, site landscaping should not cause future shading of collectors, even if they are not originally included as part of the facility. Roof construction, with regard to slope and structural concerns, should consider the possible future installation of collector arrays. In short, even if a new facility will not initially be a solar structure it should be designed with future installation of solar equipment in mind. This consideration can be extended to deciding upon the type of heating system to install in the building, e.g., if a liquid solar system may be installed in the future perhaps a hydronic heating system should be used.

3.3 Project Planning

The choice of a correct solar alternative for a particular project is determined to a great extent by whether or not it involves a new or retrofit installation.

3.3.1 New Facilities

There is a growing consensus in the solar technology community that a combination of energy conservant and passive solar design is perhaps the most cost effective way to provide solar heating to a new structure. The whole concept of using the sun's energy for space heating and DHW without pumps, fans, and controls is relatively new. When the first National Passive Solar Conference was held in 1976 few attendees believed that passive systems would work, let alone be cost effective (7). That situation has changed, and Air Force engineers and architects need to change with it. In essence, we need to learn about passive techniques and begin to employ them where and when possible in our new buildings.

The primary passive heating techniques involve direct solar gain through proper placement and sizing of southern glazing and use of thermal storage mass. Passive cooling techniques are not as advanced, but a simple and often overlooked fact in attempting to cool a facility is to remember not to heat it. Passive techniques which prevent summer solar gain (e.g., shades, window overhangs, etc.) are cheap and pay great dividends.

In summary, provision of solar energy for new facilities should include consideration of these passive techniques as well as the more familiar active systems. In order to give serious consideration to them, however, we must first know about them. It is therefore recommended that an effort be made to expose and educate our people to this recently

rediscovered and effective method to utilize solar energy. This effort can be implemented through attendance at conferences and increasing coverage of these techniques in appropriate courses at the AFIT School of Civil Engineering.

3.3.2 Retrofit Projects

If solar is to make a significant contribution to the Air Force facility energy budget, existing facilities must be augmented with solar systems. This requires retrofit projects. It is commonly held that active systems currently represent the only feasible method to utilize solar energy for existing facilities. (Passive retrofit is possible in selected cases.) Recommendations regarding the preferable types of applications for active systems were offered in Section 3.2.3. An additional cautionary thought is offered here. We should not install a retrofit solar space heating system on a facility which is not reasonably well insulated. In our zeal to implement solar we cannot permit ourselves to overlook this fundamental principle. This project demonstrated conclusively that return on reasonable energy conservation investments is much greater than that obtained from solar systems. It therefore bears repeating, never install a solar space heating or cooling system on a thermally inefficient structure.

When the decision has been made to retrofit a solar system the designer is confronted with the choice of using air or liquid collectors. There are many factors to consider in this decision but the following general comments are offered. If the primary use of the system will be to provide hot water, use liquid collectors. If the solar project will primarily be for space heating, it should be integrated into the existing heating system of the facility as effectively as possible. For example, an existing forced air convective heating system is generally more

conducive to air collectors if adequate space for the required additional ductwork and storage component is available.

Since this project involved only a liquid system, we can offer no authoritative recommendations regarding which type of installation to specify. It is our firm opinion, however, that the maintenance aspects of a system should be given much consideration. With this in mind, we are inclined to think that an air system has some intrinsic advantages. This is particularly true for locations with a freeze-damage potential. In the final analysis, the choice will likely always be a site specific variable.

3.4 Future Studies

Other agencies of the federal establishment, primarily the Department of Energy and the Department of Housing and Urban Development, are pursuing all types of energy initiatives with great vigor. The recent placement of Air Force personnel at major research centers is considered to be a good policy to foster technology transfer from these agencies. However, a word of caution is offered. We should not devote inordinate time and expense to efforts which keep us informed of latest developments in more esoteric areas (e.g., concentrating collectors, solar assisted heat pumps, etc.) when we have not yet significantly implemented more practical applications. Our current organizational efforts should more properly be focused on grassroots implementation of the more feasible, albeit mundane, technologies.

3.5 Conclusion

It is generally felt that direct thermal use of solar energy represents the most feasible and economic alternative technology that is available for widespread use. It is further believed that the basic

obstacle to its implementation by Air Force Civil Engineering and Services is institutional, and not technological, in nature. To overcome our institutional inertia is the single most critical problem we face today. To begin overcoming this problem we should mandate DHW projects on all bases located below 40^{o}N latitude. It is readily admitted that a few DHW installations on many bases are not glamorous, but it is a start, and start we must. It also happens to be the right start. It bears mentioning that the private and commercial sector is beginning to "go solar" in this area ahead of others. Recent market studies indicate that DHW installations are taking off while active space heating is stagnating (8). The public will be well served if we spend their tax dollars like they are spending their own dollars.

The recently established goal for our bases to provide 1 percent of their total energy consumption from alternative technologies by 1985 is a realistic goal and one which must be energetically pursued. Solar heating of hot water and facility floor space is the place to begin in the attainment of that goal.

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APPENDIX A

THE PERFORMANCE OF THE USAFA
SOLAR TEST HOUSE - A TECHNICAL SUMMARY

The pages which follow provide a detailed report of the solar performance of this project during the entire period of research. It is designed for the more technically inclined reader who wishes to investigate the results more thoroughly. It has also been approved for publication by the Solar Energy Division of the American Society of Mechanical Engineers.

THE CONTINUING PERFORMANCE OF THE USAF ACADEMY RETROFIT SOLAR TEST HOUSE

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ABSTRACT

This paper presents the performance of the retrofit solar space heating system which was installed on a typical military family housing unit of mid-fifties construction at the U.S. Air Force Academy. The home and the solar system were completely instrumented; system control and data storage were accomplished with an on-site microprocessor. The results presented cover the period from December 1975 to April 1979 and illustrate the effects on performance of varying the following parameters: (1) Energy conservation improvements to the home subsequent to installation of the solar system, (2) collector inclination angles, (3) collector working fluid flow rates, (4) collector flow rate control strategy, (5) storage mass and usable control temperatures, and (6) heat exchanger area between collector loop and storage. A side-by-side performance comparison of evacuated tube collectors to flat-plate collectors and an overall system performance comparison to f-Chart predictions are also included.

NOMENCLATURE

E electrical energy required to operate the solar system $(\frac{MJ}{day})$

f solar fraction (dimensionless)

I incident solar radiation $(\frac{MJ}{m^2\text{-}day})$

η_C solar collector efficiency (dimensionless)

η_S overall solar system efficiency (dimensionless)

η_T solar heating system thermal efficiency (dimensionless)

Q_C solar energy collected by the collector array $(\frac{MJ}{day})$

Q_E solar system energy losses to exterior $(\frac{MJ}{day})$

Q_U solar energy delivered to heating load $(\frac{MJ}{day})$

INTRODUCTION

It has been estimated that the U.S. Air Force consumes approximately one percent of the nation's energy (1). Of this amount, 35 percent supports a nearly unchanging inventory of facility space with heating, cooling, DHW, etc. Air Force engineers, therefore, felt that if solar energy was ever to contribute significantly to the facility energy budget that it would necessarily be through use of retrofit applications. The research conducted on this retrofit project centered on optimization of the solar system operational control parameters, verification of design parameters and acquisition of reliable performance data. Design and construction began in 1975 and the research terminated in October 1979. The results of the research have been widely reported and distributed within the Air Force (2, 3, 4, 5, 6) and to some degree in the professional community (7, 8).

SYSTEM DESCRIPTION

The Academy Solar Test House (STH) has approximately 176.4 square meters (1900 square feet) of heated floor space. A total of 50.7 square meters (546 square feet) of liquid, nonselective surface, copper absorber, double glazed, flat-plate collectors manufactured by Revere Copper and Brass Corp. were installed in the summer of 1975. Half of the collectors were placed on a due-south facing roof array permanently fixed at 52° inclination while the remaining collectors were installed on a ground array in the back of the home. The ground array also faced due south but permitted orienting the collectors at either 45°, 52°, or 60° inclination angles.

The flow pattern through the sheet and tube collectors is parallel; the 14 collector panels in each array were plumbed in parallel clusters of 4, 3, 3 and 4 collectors each. Flow within each cluster was series. The working fluid was a 50 percent (by volume) water and 50 percent ethylene glycol mixture. Each collector array loop was independent of the other and possessed its own centrifugal pump and variable valve for flow rate control.

The collector fluid transfers thermal energy via steel sheet and tube heat exchangers to an underground, 9500 liter (2500 gallon) capacity, reinforced, unlined, concrete storage tank. The tank was purposely oversized to permit investigation of various storage masses on system performance. The tank sides and top were insulated with two one-inch layers of polyurethane (approximately R-13) which was applied with hot tar. The bottom of the tank was not insulated. (This degree of insulation proved insufficient as there was too much energy loss from the tank during severe conditions.)

The storage tank water was pumped directly (no heat exchangers in the storage tank on the load side) to a water-to-air heat exchanger which was installed in the return air plenum of the existing natural gas furnace/forced-air heating system. A 42.5 m^3/min (1500 cfm) fan was used for both heating systems. A schematic of the home heating system is shown on Figure 1.

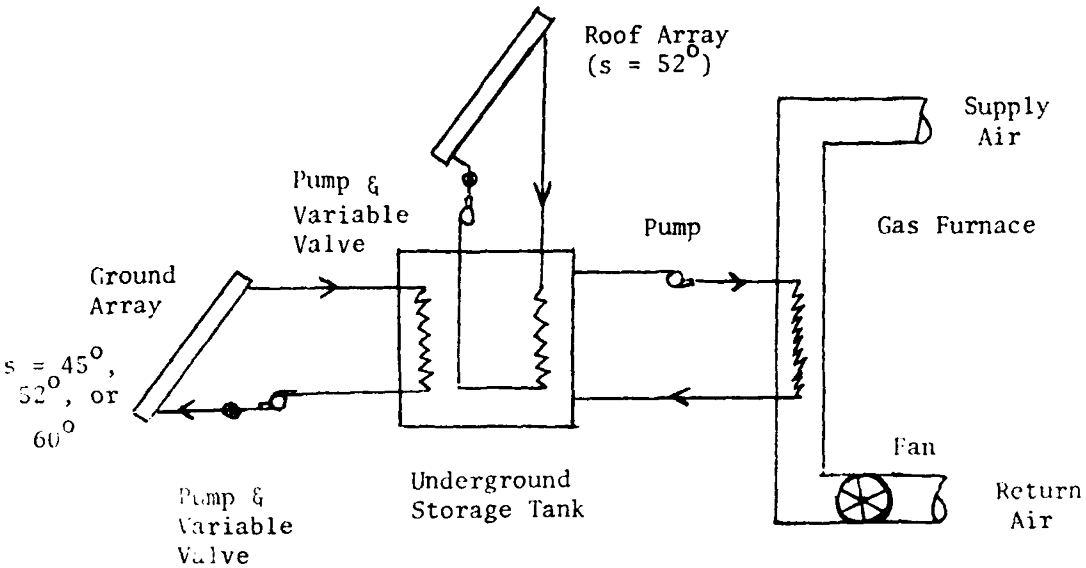

Figure 1. USAFA Solar Test House Heating System Schematic

The instrumentation and control system was an Intel Intellec 8/80 microprocessor with a teletype for printed copy and audio cassette recorders for temporary data storage. A modem interfaced the microprocessor through phone lines to a computer for data analysis and permanent tape data storage. Analog sensor inputs were collected at least every 15 minutes through an analog multiplexer and an analog to digital converter.

The microprocessor, in addition to collecting data, also controlled the home's solar and auxiliary heating systems (e.g., turned pumps and fans on and off, etc.). The control strategies were implemented in software, and operational changes were made by simply reprogramming the microprocessor. This system functioned well although most of the problems encountered during the project were associated with instrumentation and not the other components of the solar system.

RESULTS

Energy Conservation Improvements: The original design heating load of the home was 74.37 MJ/hr (70,430 Btu/hr). With more stringent interior and exterior temperature criteria in effect when the solar system was installed in 1975, the design load had decreased to 53.86 MJ/hr (51,000 Btu/hr). In February 1977 the level of insulation in the home was significantly increased. Urea formaldehyde (UF) foam was injected in all the walls and six inches of loose fill was blown into the roof joists.

The R-values of the walls and ceiling were increased from 8.2 to 15.8 and from 14.5 to 34.5, respectively. Three-inch fiberglass batts were added between floor joists over the crawl space and vestibules for the two entrances were also added during this time. The heat demand of the home calculated by standard ASHRAE procedures decreased nearly 30 percent to 38.44 MJ/hr (36,400 Btu/hr) as a result of these measures. Actual energy consumption data correlated very well with these calculated reductions. As expected, the solar fraction increased significantly after these energy conservation measures were implemented. Table 1 clearly demonstrates this result.

TIME PERIOD	SOLAR FRACTION
76-77 Heating Season:	
Oct 76-Jan 77 (pre-conservation measures)	38%
Feb 77-Apr 77 (post-conservation measures)	58%
77-78 Heating Season: (post-conservation measures)	
Oct 77-Jan 78	57%
Feb 78-Apr 78	66%

Table 1. Effect of Energy Conservation Improvements on Solar Fraction

Notice that the solar fraction increased by almost 20 percentage points for comparable time periods which contrast the home before and after the additional insulation was installed. It increased only 8 percentage points for the other time period (Feb-Apr) in which the additional insulation was installed in both seasons. This latter increase can be accounted for by operational improvements in the solar system which will be discussed subsequently in this paper. Environmental conditions, as measured by the number of heating degree days, and insolation, for all comparable time periods were very similar.

This project showed that a reasonable investment in conservation measures should be made prior to, or concurrently with, any retrofit solar modifications. A $1,125 expenditure reduced the energy consumption of the home approximately 30 percent and increased the solar fraction provided by the installed solar system nearly 12 percentage points (about 33%).

Collector Inclination Angles: A unique aspect of the collector installation for this project was the capability of the ground array to be placed at different inclination angles. The ground array was placed at 45° during the first winter of operation (75-76). On 1 October 1976 the angle was changed to 60°. On 24 May 1977 the array was again placed

at 45^o, and on 1 October 1977 it was moved to the 52^o inclination. It operated at this inclination for the remainder of the research project.

Based on the data obtained during this project it was concluded that collector efficiency did not improve as a result of more favorable inclination angles during the year. Total amounts of collected energy did increase, however, when the ground array was at more near optimum inclinations for a particular time of year. It was difficult to determine the exact increase in collected energy due solely to the angle change since other differences between the two arrays were also present.

For the angle settings tested in this project and latitude (38.8^{o}N) the collector tilts shown in Table 2 are believed to maximize collected energy.

Table 2. Recommended Collector Tilt to Maximize Collected Energy

TIME PERIOD	PREFERRED ANGLE
3 Oct - 3 Nov	52^o
3 Nov - 20 Feb	60^o
20 Feb - 3 Mar	52^o
3 Mar - 3 Oct	45^o

It must be remembered that in many, if not most, applications it may not be desirable to maximize total collected energy. In a space heating application, for example, summer time gain should be minimized to help prevent overheating. It should also be noted that during high load periods (3 Nov - 3 Mar) that the 60^o tilt maximized collected energy 90 percent of the time (approximately 110 days out of the 120 day period). This inclination corresponds to latitude plus 21^o, not the often recommended rule of thumb of latitude plus 10^o-15^o. It is nevertheless felt that use of these recommended compromise tilts will not greatly affect system performance. Another consideration which must not be forgotten is the greater cost involved in constructing and operating a movable array. Changing the angle required a 3-4 man crew for approximately one hour.

Collector Working Fluid Flow Rates: Both collector arrays had identical pump and valve arrangements. The flow rate through each array was controlled by a motor driven variable valve which was activated by the microprocessor. The pumps were purposely oversized (1/2 hp each) to permit a wide range of available flow rates to both arrays. The arrangement permitted flows of .126 - 1 liter/sec (2-16 gpm) to each array.

During the first winter of operation (75-76) the flow to each array was permitted to reach 1 liter/sec (16 gpm) at full open position. This equated to an average rate of approximately .04 liter/sec per square

meter of collector area (.06 gpm/square foot). This flow rate resulted in extremely high collection efficiencies, sometimes reaching 70 percent.

Prior to the second winter the maximum flow rate was cut in half. The effect of this reduction on the working fluid temperatures was immediate. Prior to the change a good collection period would result in a 6°C (10°F) fluid temperature rise whereas afterwards it would sometimes reach 11°C (20°F). The higher temperature differential was, of course, obtained at the expense of reduced collector efficiency. This sacrifice was worthwhile since it helped to increase storage tank temperatures. Consequently, the usability of storage for home heating was improved. In essence, collector efficiency was sacrificed to improve system efficiency and to achieve a higher solar fraction. The flow rate which optimized system performance for this project was .25 liter/sec (4 gpm) or .01 liter/sec per square meter (.015 gpm/square foot). This rate resulted in average collection efficiencies of 20-40 percent during the heating season. Even with these much lower collector efficiencies, however, more solar energy was delivered to the home.

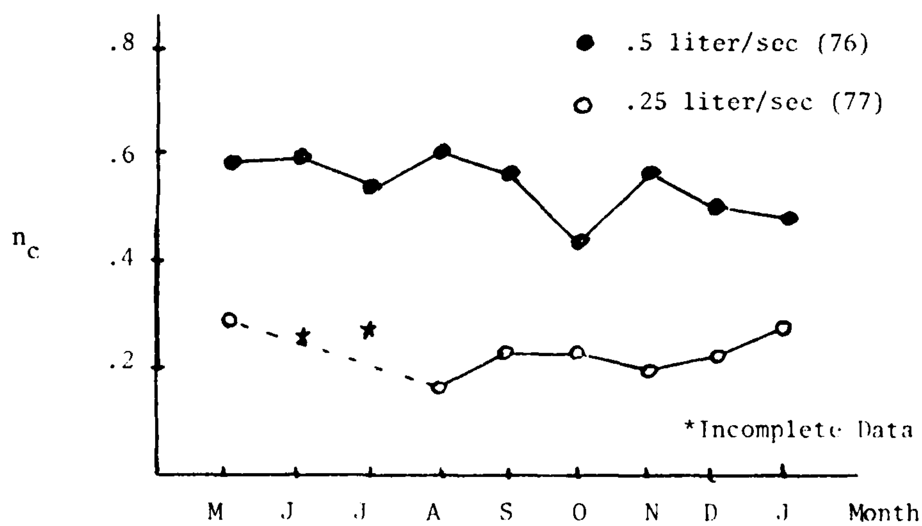

Figure 2. Effect of Working Fluid Flow Rate on Collector Efficiency

Collector Flow Rate Control Strategy: The microprocessor-controlled variable valves in the collector loops permitted investigation of optimized control strategies. An optimal flow rate strategy is opposed to the more conventional "on-off" strategy which provides for only two settings -- either complete shutdown or full open to the desired maximum flow rate.

The optimization strategy which finally developed was as follows: When the collector plate temperature (sensed at geometric center) was 12°C (20°F) higher than storage, the variable valve opened to its midsetting (i.e., one half of the desired full open rate) and the pump would come

on. Control then switched to a comparison of collector fluid exit temperature to storage temperature. When this temperature difference reached 1.7°C (3°F) or less, the variable valve would continue to close incrementally until it reached one-fourth of full open at which time shutdown of the pumps would occur. Higher valve settings would likewise occur if the ΔT between exit and entry temperatures was 6°C (10°F) or greater.

This control strategy provided two benefits. First, the reduced flow rates imposed during shutdown typically extended the collection period about 15-30 minutes. During these periods, however, conditions were marginal and not much total energy was being collected. Storage tank temperature increases were extremely rare during the shutdown sequence. Secondly, collector efficiency was improved by forcing higher flows if the ΔT across the collectors exceeded 6°C (10°F). Once again, however, analysis of the data indicated that only short periods of collection existed where this strategy could have represented an improvement over a "bang-bang" full open setting.

It should be noted that this strategy may not have been necessarily optimal; it could have provided more energy under some conditions but not under others. At no time for example, did we attempt to include the costs of parasitic pump power in the control algorithm. As a result of experience gained with this system, it is felt that a simple on-off control at a fixed flow rate would have proven acceptable in all but marginal conditions. To implement a variable control strategy probably requires a microprocessor-based control system and some type of motor driven variable valve. Simplicity is improved and extra expense avoided if a simple on-off strategy is used. Accordingly, when research terminated and the home was returned to the normal base housing inventory, a conventional "bang-bang" control scheme was employed. The system continues to function well with this strategy.

<u>Storage Mass Variations and Control Temperature Changes</u>: During the first winter of operation the storage tank was nearly filled to its 9500 liter (2500 gallon) capacity. In July 1976 the volume was reduced to 6800 liters (1800 gallons). This reduction had the immediate effect of making the tank temperature more responsive to the energy input from the collectors. This was significant since during the first winter the collectors would often operate all day but the storage temperature would not reach usable levels. In August 1977 the storage volume was further reduced to 5300 liters (1400 gallons). These storage mass reductions probably worked in combination with the intentionally reduced collector flow rates discussed previously, to lower collector efficiency.

A parameter closely related to storage mass is the minimum temperature at which it can be used to supply energy to the load. This project initially required a 41°C (105°F) temperature in storage. This temperature resulted in approximately 31.5°C (88-89°F) air at the home's heating registers. In order to use lower temperature energy an investigation was made to determine the lowest usable storage temperature which would result in no occupant discomfort. The control temperature was subsequently reduced 26.7°C (80°F) air at the registers. No occupant complaints were

made, although installation of linear diffusers at all registers is believed to have helped prevent any discomfort.

The impact of these measures on system thermal efficiency is shown in Figure 3. Unfortunately we were unable to further reduce the storage mass due to plumbing limitations of the collector loop heat exchangers. Had we been able to do so, the thermal efficiency would have probably peaked, and subsequently decreased, around the generally accepted value of 50-75 kg/m^2 (approximately 1.5 gal/ft^2) which has been reported by other investigators (9). There are many factors which impact thermal efficiency but the storage component, since it connects energy collection to the load, is believed to have had a great effect in this project.

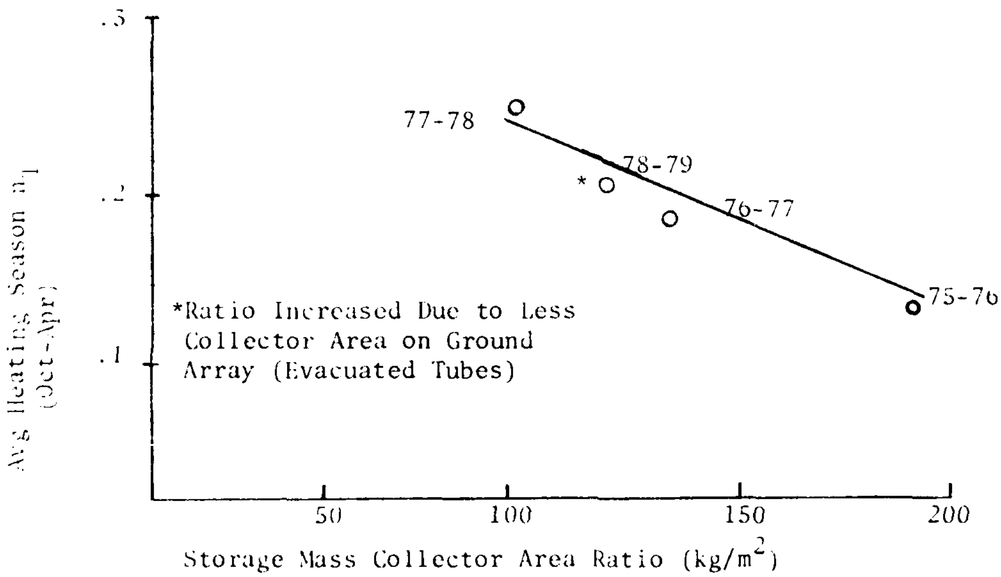

Figure 3. System Thermal Efficiency vs Storage Mass

Heat Exchanger Area in Storage: Each collector array loop was interfaced with storage via two flat, steel, serpentine flow (ea 1.1 square meters in area; 11.9 square feet) heat exchangers. The heat exchangers were plumbed in parallel for each array. During the first winter of operation it was noticed that a significant difference existed between the storage and the collector fluid entry temperatures. Since this indicated poor heat transfer, a third identical heat exchanger was added to the ground array loop in the summer of 1976.

The addition of this heat exchanger resulted in a reduction of the ground array average working fluid temperature. The ΔT across the array remained the same but the entire loop tended to more nearly approach the storage tank temperature. This resulted in the ground array collectors

running cooler and therefore more efficiently than the roof array. The following data support this conclusion. Prior to the installation of the additional heat exchanger, the ground and roof array collection efficiencies for the period February-May 1976 were 56.4 and 58.8 percent respectively. For the same period in 1977 after installation of the additional heat exchanger for the ground array, the efficiencies were 46.8 and 35.9 percent respectively. Note that the average efficiencies for the arrays decreased in the later time period since flow rate decreases had also occurred.

Significant corrosion and mineral scale deposition on the exchangers had occurred. Dielectric unions were used between the copper piping and steel exchangers and were deemed effective in preventing galvanic corrosion. Uniform, exterior corrosion was the main problem. Inhibitors were never added to the storage water but their use may be warranted. The heat exchange effectiveness has no doubt deteriorated due to these problems. This consideration, along with the need to achieve maximum heat transfer to storage, seems to make a liberal approach to heat exchanger sizing advisable

Evacuated Tube Collector Installation on Ground Array: Many advantages have been claimed for evacuated tube collectors. They reportedly achieve higher efficiencies and higher fluid temperatures under many operating conditions. They are also supposed to outperform flat-plates in marginal conditions. In order to test their performance in this project, the ground array, beginning in October 1978, was equipped with 12 General Electric Model TC-100 evacuated tube collectors. Only 17.8 square meters (192 square feet) of collector area was installed versus the 25.4 square meters (273 square feet) for the previously installed flat-plates. The 52° inclination angle was not changed in order to permit performance comparison with the formerly installed flat-plates and also with the flat-plates which remained on the roof array.

The performance of the collector arrays before and after the evacuated tubes were installed is shown in Figure 4.

Note that the ground array consistently outperformed the roof array while both arrays possessed flat-plates. This was considered to be primarily due to the presence of the additional heat exchanger on the ground array loop which was discussed in the preceding section. After changing the ground array to evacuated tube type collectors, the collection efficiencies reversed. The overall efficiency of the flat-plate system from May-August 1978 was 33.1 percent with 23.3 GJ (22.1 x 10^6 Btu) collected from 70.3 GJ (66.7 x 10^6 Btu) available. The efficiency of the evacuated tube-ground array (October 78-March 79) was 25 percent with 13.2 GJ (12.5 x 10^6 Btu) collected from 52.7 GJ (50 x 10^6 Btu) available. The flate-plate-roof-array efficiency during the same period was 38.3 percent with 23.9 GJ (22.7 x 10^6 Btu) collected out of 62.5 GJ (59.3 x 10^6 Btu) available. The overall efficiency of the "mixed arrays" from October 1978 to March 1979 was 32.2 percent. The flat-plate collectors on the roof array contributed 64.5 percent of the energy collected during this period; they represented 58 percent of the installed gross collector area. The flat-plates were operated at a flow rate of .01 liter/sec per square meter

(.015 gpm/square foot) which was believed to be optimum for this project. The evacuated tubes were operated at .008 liter/sec per square meter (.013 gpm/square foot) which was within the manufacturer's recommendations.

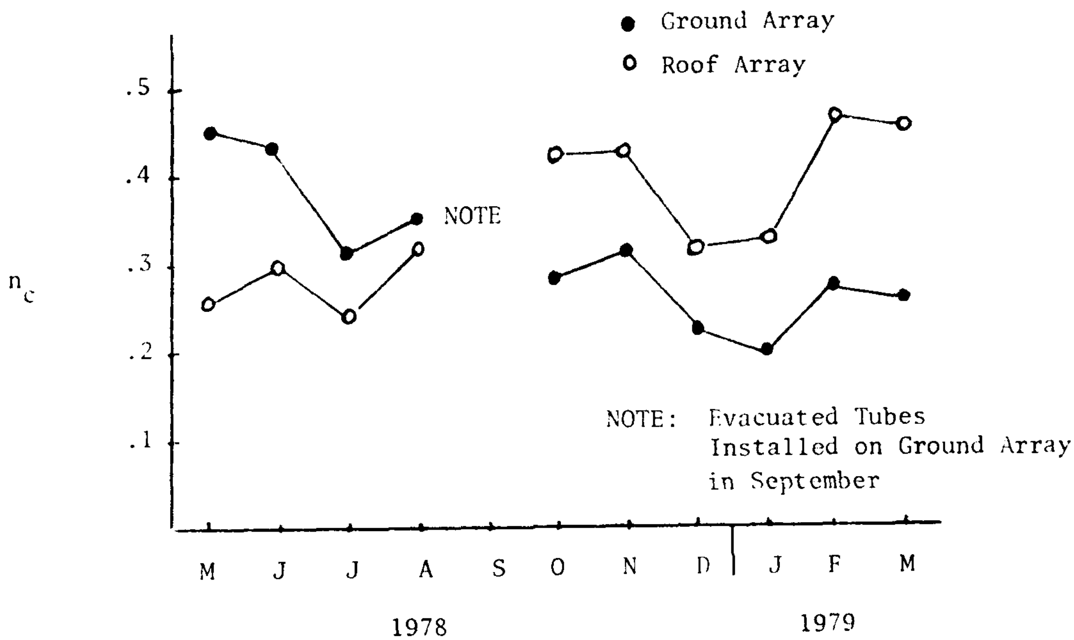

Figure 4. Evacuated Tube vs. Flat-Plate Collector Efficiency Comparison

Very little evidence was available to support the view that evacuated tubes perform better than flat-plates during marginal conditions. They did begin operation earlier in the day but some cycling was experienced. They would generally remain on at the same time as the flat-plates would start up. Contrary to expected behavior was the fact that the evacuated tubes would shut down earlier at the end of the collecting day. In addition, the evacuated tubes did not operate on any day in which the flat-plates didn't. In fact, several instances of the flat-plates running longer than the evacuated tubes on cloudy days occurred.

Installation and maintenance requirements were significantly greater for the evacuated tubes. Greater care and better quality solder is required during installation to prevent development of leaks in the plumbing system as a result of localized high pressure conditions during stagnation. (Leaks occurred on this project despite the presence of a pressure relief valve.) Some glass shrouds broke for no apparent reason and some broke as a result of thermal shock after stagnation conditions. Their replacement, though not difficult, was a time-consuming task and an irritant.

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In sum, the evacuated tubes' performance in this application and location was not as good as the flat-plate collectors. It must be remembered, however, that evacuated tube efficiency curves tend to be flat. The relatively low temperature application that existed in this project may not have taken advantage of this characteristic. Other system parameters, such as a probable oversized storage mass, could have decreased their performance also.

Comparison with f-Chart Predictions: Measured solar fractions for the third heating season (77-78) and total annual performance (September 1977-August 1978) is compared to f-Chart predictions in Figure 5. The last winter of operation (1978-1979) was not used due to the evacuated tube collectors on the ground array. Earlier periods were also excluded since they involved considerable operational experimentation (oversized storage mass, high collector flow rates, etc.) which resulted in less than optimum performance.

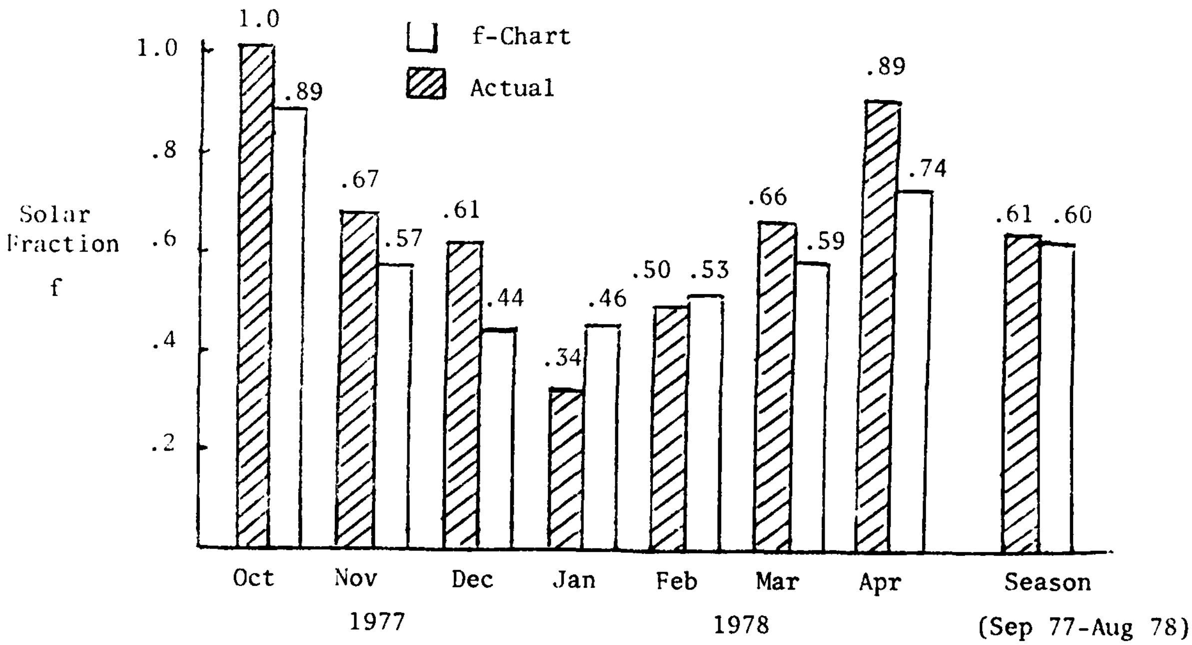

Figure 5. Comparison of Actual Solar Fractions to f-Chart Predictions

The f-Chart predictions are based on weather data for nearby Colorado Springs which are stored in the latest computer program version (Version 3) of the model. The individual months show considerable discrepancy but the annual contributions are in excellent agreement. Although the degree of this agreement is probably somewhat coincidental, it indicates that f-Chart can be used with some degree of confidence to predict annual solar contributions.

PERFORMANCE

This solar system performed relatively well. The annual solar fraction will approach 60 percent in a typical year when the system is operated and maintained in good order.

Figure 6 shows the average daily insolation (by month) available to the collectors and the amount of energy they collected. A slight downward trend in available energy was present throughout this period. Figure 7 shows the collection efficiency over the entire period of record. Note the decreased efficiency trend; this was due to the lowered flow rates and the installation of the evacuated tubes which was discussed earlier.

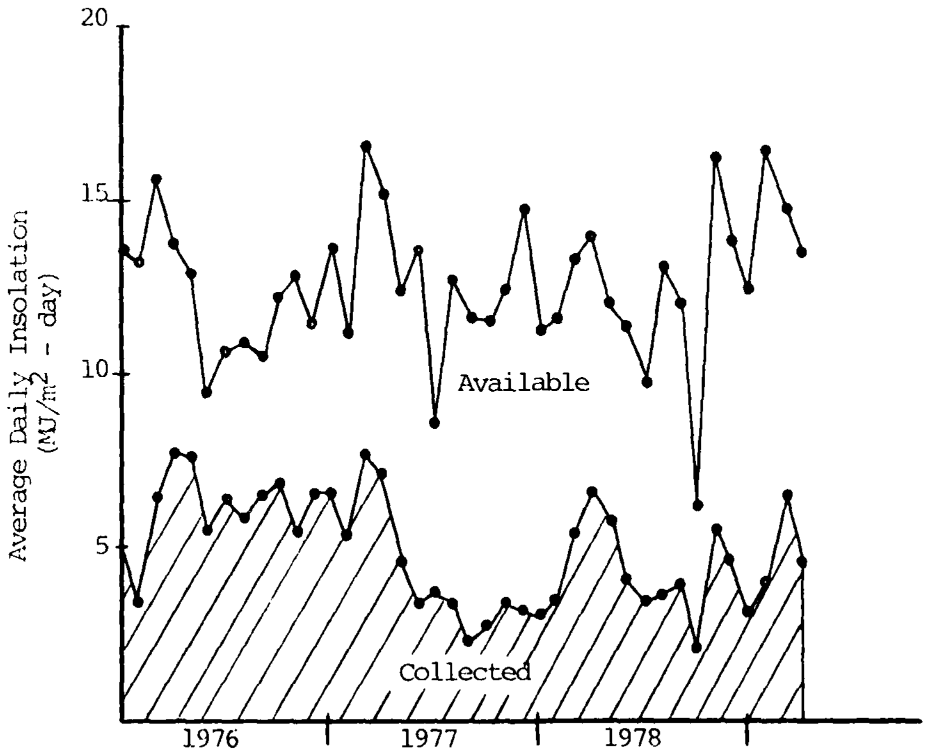

Figure 6. Solar Energy Available and Collected

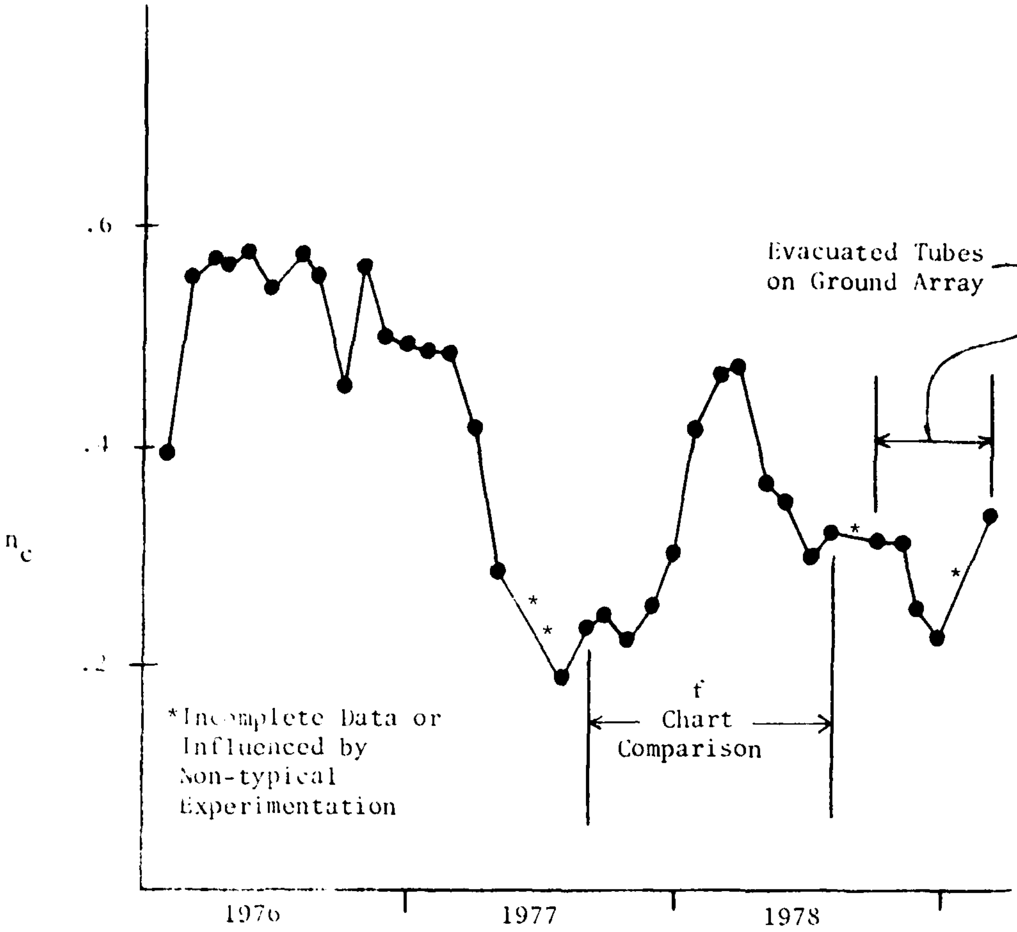

Figure 7. Monthly Collection Efficiency (n_c)

Figure 8 shows the heating degree days, the house heating demand and the solar fraction. In general, the winters became increasingly severe. The energy demand follows the degree-day plot fairly closely most of the time. The effect of the increased insulation (installed in February 1977) can be seen by comparing the demand in March, April, and May 1976 to tnat experienced in 1977. Even though the degree-days were nearly equal in those months in 1977, the energy demand of the home was greatly reduced. This reduction of the "demand to degree-day ratio" continued until February 1978 when it increased significantly. This can be seen by comparing the months of March and April in 1978 to 1977. The primary reason for this change was that the home became vacant in January 1978. (It remained unoccupied for the duration of the research project.) It is believed that the energy gains associated with normal occupancy are significant in the total energy budget of a well insulated, residential structure.

Close examination of Figure 8 shows that the amount of solar energy provided to the home during the heating seasons (October-April) continually increased over the first three winters of operation. This improved performance occurred primarily as a result of operational changes which have been previously discussed. The solar system continued to provide a large amount of energy in the last winter of record, but direct comparisons are difficult due to the lower-efficiency evacuated tube

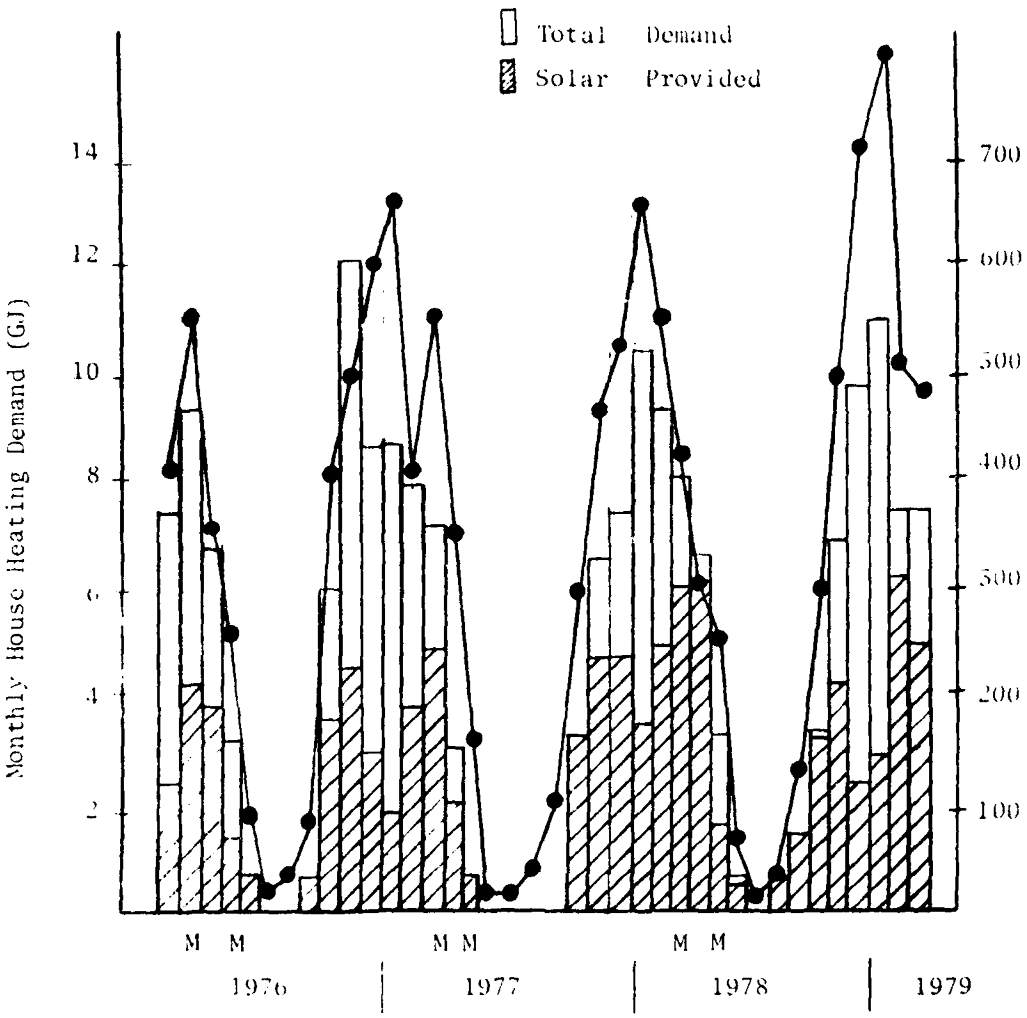

Figure 8. Heating Demand, Solar Fraction and Degree Days

collectors which were installed on the ground array. It must also be remembered that 15 percent less collector area was in use during this period.

Table 3 gives a performance summary for this project for each heating season. Table 4 extracts salient information from Table 3 for use in a closing discussion of this system's performance.

CONCLUSION

Table 4 shows that the third winter of operation achieved the highest thermal efficiency and solar fraction. Other conclusions are as follows. In general, column one reflects the purposeful decrease in collector efficiency which was obtained by lowering collector flow rates and storage volume. These actions led directly to higher temperatures in the storage tank. Column two reflects the consequent increased usability of storage in providing energy to the home. The solar fraction and system thermal efficiency steadily increased the first three winters as a

Table 3. ACADEMY STH SOLAR SYSTEM PERFORMANCE RESULTS

TERM	TIME	OCT	NOV	DEC	JAN	FEB	MAR	APR	SEASON AVG.
I $\frac{MJ}{day\text{-}m^2}$	1	--	--	13.6	13.1	15.6	13.8	12.9	13.8
	2	12.8	11.4	13.6	11.1	16.4	15.2	11.9	13.2
	3	12.2	14.8	11.1	11.6	13.2	13.9	12.1	12.7
	4	16.2	13.8	12.4	16.4	17.2	13.4	--	14.9
Q_c $\frac{MJ}{day}$	1	--	--	*256.1	*171.8	324.7	395.8	390.0	370.2
	2	276.0	334.4	333.4	266.7	394.8	358.3	248.0	315.9
	3	167.2	157.0	154.0	191.4	273.1	333.8	293.3	224.2
	4	241.9	203.0	133.9	172.8	*280.8	203.0	--	205.9
η_c	1	--	--	.37	.26	.41	.56	.59	.52
	2	.43	.58	.48	.47	.47	.46	.41	.47
	3	.27	.21	.27	.32	.41	.47	.48	.35
	4	.34	.34	.25	.24	*.38	.35	--	.32
Q_u $\frac{MJ}{day}$	1	--	--	29.9	37.6	110.1	141.8	134.8	90.8
	2	121.4	156.3	133.2	111.2	137.3	147.6	79.4	126.6
	3	120.1	146.5	142.8	113.1	166.0	180.9	202.8	153.2
	4	111.3	136.1	82.1	100.4	*221.2	153.2	--	134.1
Q_E $\frac{MJ}{day}$	1	--	--	*226.2	*134.2	214.6	254.0	255.2	216.8
	2	154.6	178.1	200.2	155.5	257.5	210.7	168.6	189.3
	3	47.1	10.5	11.2	78.3	107.1	152.9	90.5	50.0
	4	130.6	66.9	51.8	72.4	59.6	49.8	--	71.8
η_T	1	--	--	.043	.06	.14	.20	.20	.14
	2	.19	.27	.19	.20	.16	.19	.14	.19
	3	.19	.25	.25	.19	.25	.26	.33	.25
	4	.16	.23	.15	.14	*.30	.26	--	.21
f	1	--	--	.09	.11	.36	.45	.57	.27
	2	.60	.44	.34	.24	.44	.66	.74	.45
	3	1.0	.67	.61	.34	.50	.66	.89	.61
	4	.94	.59	.27	.29	*.82	.63	--	.53
L $\frac{MJ}{day}$	2	27.8	26.1	37.5	49.3	31.8	31.7	27.0	33.0
	3	26.6	26.9	25.5	20.8	33.1	28.7	28.8	27.2
η_S	2	.14	.23	.14	.11	.13	.15	.09	.14
	3	.15	.16	.21	.16	.20	.22	.28	.18

Time 1 = First Winter (76-76)
Time 2 = 2nd Winter (76-77)
Time 3 = 3rd Winter (77-78)
Time 4 = 4th Winter (78-79)

*Partial data or influenced by non-typical experimentation. Note that considerable start-up difficulty with the instrumentation system was experienced in the first winter.

result of these operational improvements and energy conservation measures installed on the structure. The decrease in solar fraction and thermal efficiency in the last winter is attributed to the decreased collector area and the lower-efficiency evacuated tube collectors that were installed on the ground array. Note that Table 3 reveals that the third winter also attained the highest overall system efficiency (n_s).

This project has provided valuable operational and maintenance experience on solar heating systems for the Air Force. In addition, much reliable performance data has been obtained which will allow more knowledgeable decision-making regarding the application of solar energy to the Air Force's present and future facility energy requirements.

Table 4. Solar System Thermal Performance Summary

Time Period	n_c	Q_U/Q_c	f	n_T
First Winter (Dec 75-Apr 76)	.52	.30	.27	.14
Second Winter (Oct 76-Apr 77)	.47	.40	.45	.19
Third Winter (Oct 77-Apr 78)	.35	.70	.61	.25
Fourth Winter (Oct 78-Mar 79)	.32	.65	.53	.21

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